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THE INFLUENCE OF SILT ON THE COMPRESSIBILITY OF AN
ILLITIC CLAY

BY
JAMES INMAN SPENCER, 1939

A
THESIS

132978

submitted to the faculty of
THE UNIVERSITY OF MISSOURI AT ROLLA
in partial fulfillment of the requirements for the
Degree of
MASTER OF SCIENCE IN CIVIL ENGINEERING
Rolla, Missouri
1968

Approved by

Thomas S. Fry (advisor) Marion O. Schmidt
G. B. Anglenbaugh

TABLE OF CONTENTS

	Page
LIST OF FIGURES	iii
SYNOPSIS	1
INTRODUCTION	2
MATERIALS AND TESTING PROCEDURE	3
DISCUSSION OF RESULTS	8
CONCLUSIONS	21
ACKNOWLEDGEMENTS	26
VITA	27
APPENDIX (Dial Reading - \log_{10} Time Curves)	28

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1 Percent Finer - Grain Size Curve	4
2 Sedimentation Chamber	6
3A Void Ratio - \log_{10} Pressure Curve (0 and 20 Percent Silt)	12
3B Void Ratio - \log_{10} Pressure Curve (40 and 60 Percent Silt)	13
3C Void Ratio - \log_{10} Pressure Curve (70, 80 and 100 Percent Silt)	14
4 Strain - \log_{10} Pressure Curve	16
5 Liquid Limit - Compression Index Curve	17
6 Liquid Limit - Percent Silt Curve	19
7 Percent Silt - Compression Index Curve	20
8 Water Content - Percent Silt Curve	22
Appendix Dial Reading - \log_{10} Time Curves	28

TABLES

<u>Table</u>	
1 Properties of Compressibility	11

THE INFLUENCE OF SILT ON THE COMPRESSIBILITY OF AN
ILLITIC CLAY

By James I. Spencer¹

SYNOPSIS

This study was undertaken to investigate the effect of varying amounts of clay (illite) on the compressibility of a silt as it may be found in nature in a normally consolidated deposition. Laboratory procedure was designed to minimize sample disturbance so as to obtain, as nearly as possible, a virgin consolidation curve. By varying the amounts of silt and clay in a given sample, and sedimenting the sample from a soil-water suspension, consolidation test analyses were used for a comparison of the various samples. Results revealed that between sample mixtures of 40 and 60 percent silt there was a relatively large change in the proportionality of compression index to liquid limit, and that the compression index varied directly with the percent silt present in the sample. A method of predicting settlement characteristics from existing water content, overburden pressure and percent silt was also suggested. Furthermore, it was evident that small changes in silt content had a considerable effect on the consolidation time of silt-clay mixtures.

1. Candidate for the Degree of Master of Science in Civil Engineering at the University of Missouri at Rolla, Rolla, Missouri.

INTRODUCTION

One problem which always must be considered in the design of foundations, is the allowable settlement under a given set of conditions. Much laboratory and field experimentation has been accomplished in this area of Soil Mechanics and Foundation Engineering and it is possible today, with the tools made available through previous research, to predict settlements with reasonable accuracy.

Most of the theories and empirical techniques for computing settlement, currently available, were developed for soil deposits where one major type, either sand or clay, was assumed to predominate. The use of these same techniques for soils of mixed classification has been fairly common practice even though it has been recognized that mixtures do not necessarily behave in a manner similar to those soils that are considered relatively pure or ideal.

In this investigation, varying percentages of silt and clay soils were mixed and subjected to consolidation tests for the purpose of investigating the influence of these basic constituents on the compressibility of a combined soil. Test samples were prepared in a sedimentation apparatus designed to provide specimens in a normally consolidated condition with a water content near the liquid limit. Undisturbed specimens were subjected to one dimensional consolidation with load increments increasing to 16 kilograms per square centimeter. The resulting data was analyzed to determine the variation in behavior of the different mixtures.

MATERIALS AND TESTING PROCEDURE

The silt used in this study, a light brownish grey material, was sufficiently processed to eliminate most non-silt soil sizes. The grain size varied uniformly between 0.05 millimeters and 0.01 millimeters, which places it in the coarser region of the grain size classification for silt (Fig. 1).² Approximately 12 percent varied between 0.002 and 0.01 millimeters. The specific gravity of the material was approximately 2.62 and the D_{50} size was 0.019 millimeters.

The clay fraction was illite purchased from a commercial source under the name of Grundite. It was grey in color and floury in texture, with a liquid limit of 56 percent,² a plasticity index of 27 and a specific gravity of approximately 2.66.

Silt-clay samples were mixed with 0, 20, 40, 60, 80 and 100 percentages of silt, by weight, per total sample. After the initial pattern was exhibited by the consolidation test results, a sample of 30 percent silt - 70 percent clay also was tested. Experimentation revealed that approximately 85 grams dry weight of material would provide test samples within a reasonable range of initial heights for use in the consolidation test. Initial sample heights varied approximately 0.1 inch with an average initial height of about 0.65 inches. It has been shown by Van Zelst³ that sample thicknesses within the range used provide sufficiently accurate data for settlement analysis.

2. Jackson, A. T., "Shear Strength Behavior in Silt and Clay Mixtures", Research Thesis for the degree of Master of Science in Civil Engineering, University of Missouri at Rolla, Rolla, Missouri 1968

3. Van Zelst, T. W., "An Investigation of the Factors Affecting Laboratory Consolidation of Clay", Proc. Second Int. Conf. on Soil Mechanics and Foundation Engineering, Vol. III, Rotterdam 1948

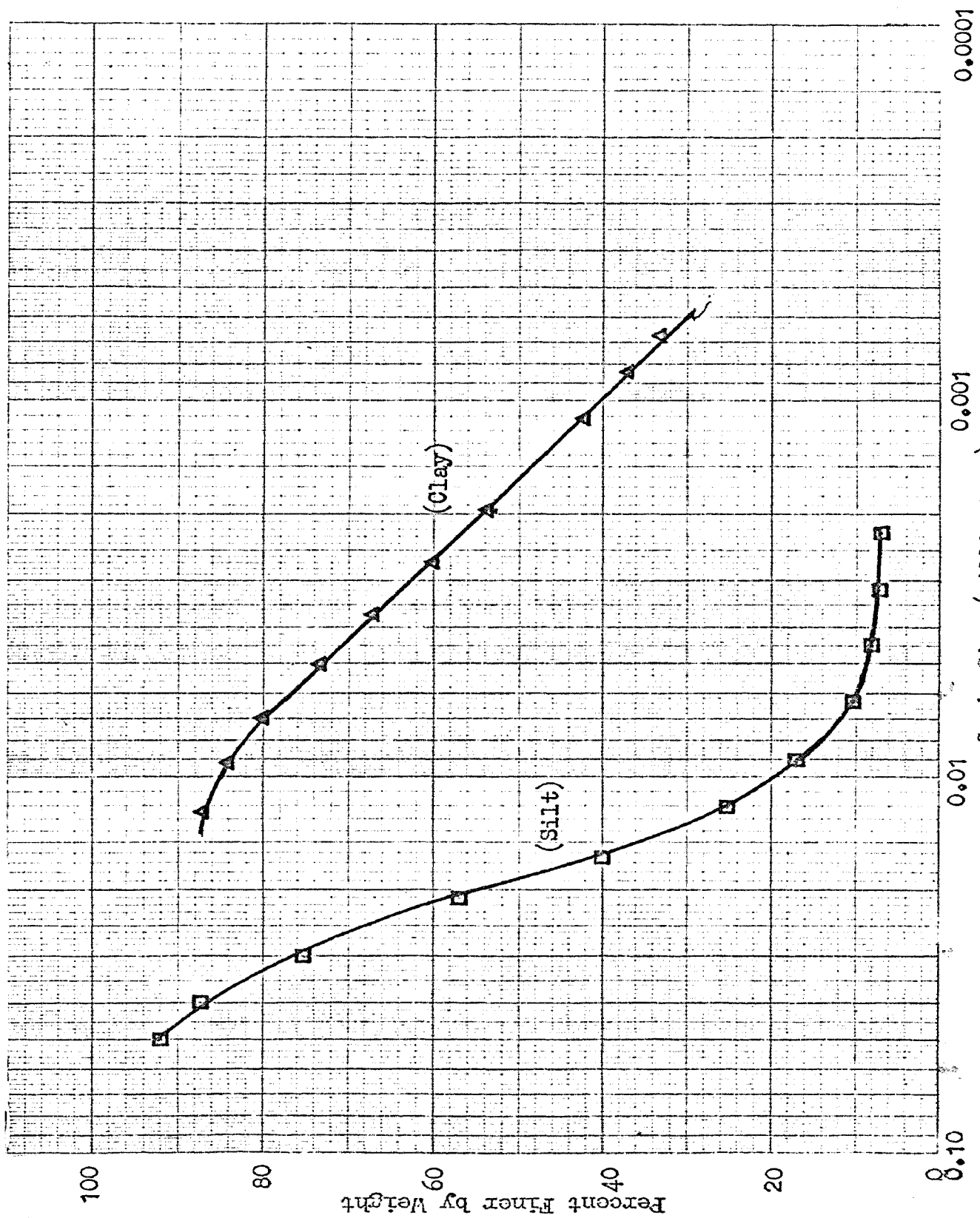
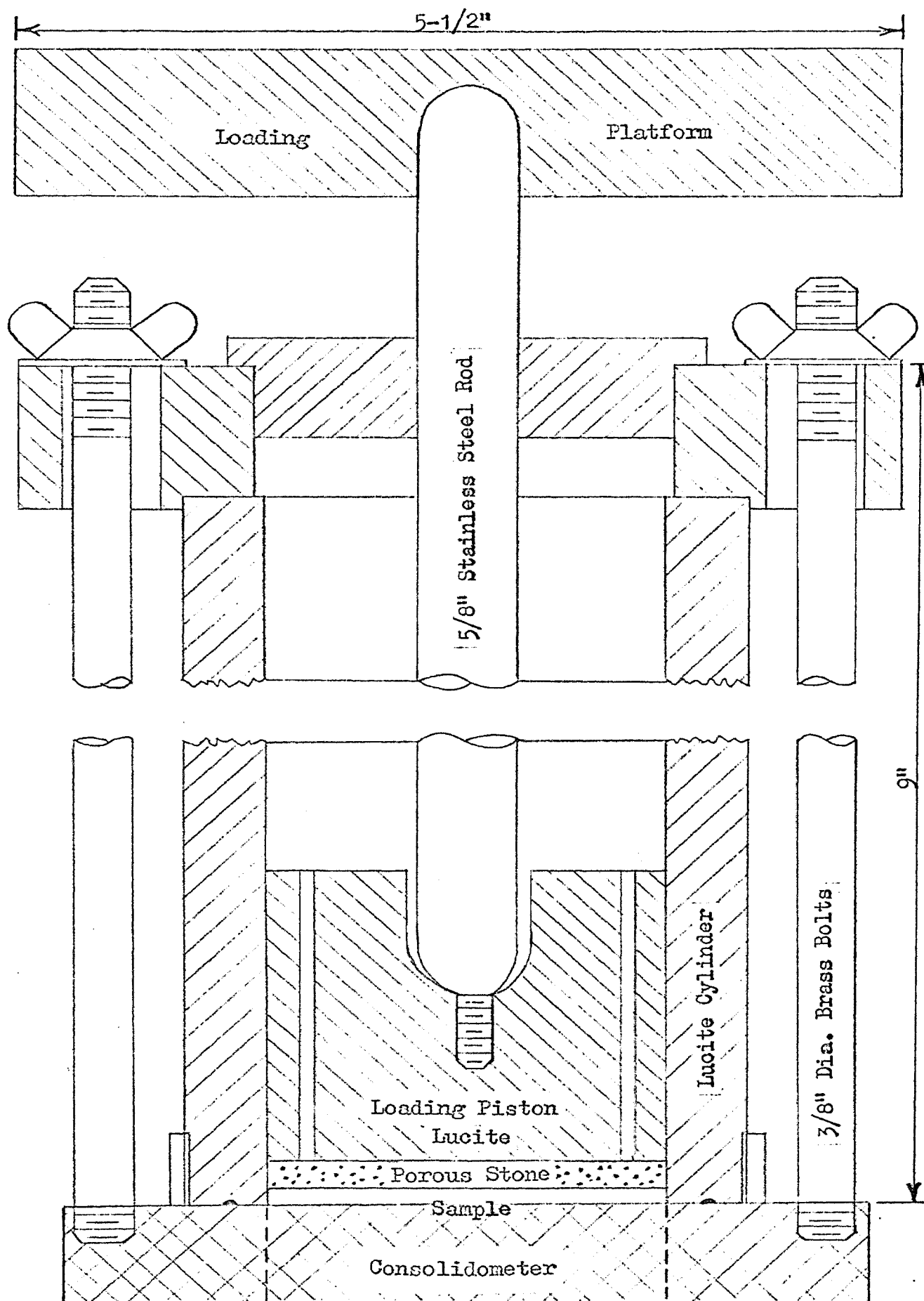


FIGURE 1
PERCENT FINER - GRAIN SIZE CURVE

In order to obtain an undisturbed sample for testing, the silt-clay mixture was sedimented under pressure, from a soil-water slurry, directly into the consolidation apparatus. This also provided a normally consolidated condition.

Sample preparation was accomplished using the following fixed procedure. Appropriate percentages of silt and clay materials, having a total dry weight of 85 grams, were placed in a 1000 milliliter graduated cylinder and mixed into a slurry with sufficient water so that the mixture could easily be poured, but not so wet as to allow segregation. The soil-water mixture was transferred to a sedimentation device capable of applying an axial pressure through a loading piston (Fig. 2). The sedimentation chamber was affixed to a consolidometer so that the sample would be formed in the consolidation ring. The inside of the sedimentation cylinder was coated with an inert silicone oil⁴ to provide lubrication and to insure adequate seal between the loading piston and the cylinder. The base of the loading piston was affixed with a standard consolidometer porous stone and filter paper. Small holes (0.10 inches) were drilled through the loading piston to permit vertical drainage from the top of the sample through the porous stone and the loading piston. Drainage was also permitted through the porous stone in the base of the consolidometer. The total load applied to form the sample from the soil-water suspension was 2004 grams, which was approximately 25 percent of the initial pressure increment applied during the consolidation test. Consequently, all pressure increments

4. L - 45 Silicone, Viscosity = 100 cstks.



SEDIMENTATION CHAMBER

FIGURE 2

applied during the consolidation tests resulted in virgin compression of the sample. The sedimentation process was allowed to continue until no appreciable movement of the loading platform could be measured. This required from four to eight hours, depending on the amount of clay present in the samples. After completion of this initial consolidation the sedimentation chamber was removed and a standard consolidation test was performed. The filter paper located between the loading piston porous stone and the sample remained in place when the piston was removed and was used during the consolidation test.

The only problem encountered with the sedimentation device was a small amount of extrusion of the sample around the upper porous stone and loading piston, which resulted in a loss of a small percentage of the solids. This loss of material had no significant effect on the test results.

All samples obtained were consolidated to an initial height below the top of the consolidation ring, thereby alleviating the necessity of sample trimming. This minimized sample disturbance. Initial void ratios of the samples ranged from 1.53 for 100 percent clay samples to 0.86 for a mixture of 70 percent silt and 30 percent clay. The 100 percent silt sample had an initial void ratio of 0.90. The initial void ratios of the samples with a predominance of silt corresponded closely to observed natural void ratios of Loess deposits with a predominance of silt size particles⁵

5. Bolognesi, A. J. L., and Moretto, O., "Properties and Behavior of Silty Soils Originated from Loess Formations", Proc. Fourth Int. Conf. on Soil Mechanics and Foundation Engineering, Vol. I, London, 1957.

Weight-volume relationships could not be determined until the end of the consolidation tests because the extrusion of solid material during sample forming prevented an accurate determination of initial sample weights. Although no check could be made, saturation was assumed throughout since samples were formed from an initially suspended condition.

Consolidation tests were conducted using a standard Casagrande fixed ring consolidometer with a ring diameter of 2.5 inches. Tests were performed according to the procedure outlined by Lambe⁶ with pressure increments of 1/4, 1/2, 1, 2, 4, 8 and 16 kilograms per square centimeter. Rebound pressures used were 4, 1 and 1/4 kilograms per square centimeter, ending with the seating load. Initial and final seating loads were 2004 grams, 64 grams per square centimeter, which was identical to the load under which the initial sample sedimentation was performed.

DISCUSSION OF RESULTS

To facilitate discussion, the test results for samples will be divided into three groups. Group one includes tests on mixtures that were predominately clay, group two includes tests on mixtures that were intermediate in range (40 and 60 percent silt and clay) and group three includes tests on mixtures that were predominately silt.

6. Lambe, W. T., Soil Testing for Engineers, J. Wiley and Sons Inc., New York 1960.

Dial reading - \log_{10} time curves exhibit typical shapes which would be expected for the mixtures tested. All curves are generally parallel throughout the primary and secondary compression ranges. It is interesting to note however, that all samples, except those of 80 and 100 percent silt mixtures, exhibited a noticeable departure from this parallelism within one pressure increment. For the 100 percent clay sample it was the $1/2$ kilogram per square centimeter pressure and for other samples it was the $1/4$ kilogram per square centimeter increment. This difference in compression curves can logically be explained by the fact that partially flocculated structure must have been formed in these samples during the sedimentation process, and under the influence of the pressures indicated, the structures collapsed. This apparent breakdown of structure is quite evident in the 100 percent clay sample (Fig. 1A - Appendix) and this effect tends to decrease in proportion to the amount of silt present in the sample. The sample of 70 percent silt - 30 percent clay (Fig. 5A - Appendix) exhibits only a slight indication of this process and it was absent altogether in the 80 and 100 percent silt samples.

Those samples containing 60 percent or more silt consolidated very rapidly. To obtain data required for calculations it was necessary to use the Taylor method of curve fitting which uses dial readings versus square root of time, rather than the more common Casagrande method which uses dial readings versus \log_{10} time.

The square root of time method, however, did not provide precise results for the samples of group three. Consolidation was so rapid that determination of 0 and 90 percent consolidation times could only be approximated. The plot of these samples by the \log_{10} time method revealed merely the straight line portion of secondary consolidation (Figs. 5, 6 and 7 - Appendix).

A comparison of 90 and 100 percent primary consolidation times (t_{90} and t_{100}) revealed that the presence of any amount of silt has a marked influence on the behavior of clay. The t_{100} for 100 percent clay averaged approximately 30 minutes. The addition of 20 percent silt reduced t_{100} to approximately eight minutes. All samples within group three exhibited 90 percent consolidation times (t_{90}) within a range of 0.1 to 0.25 minutes.

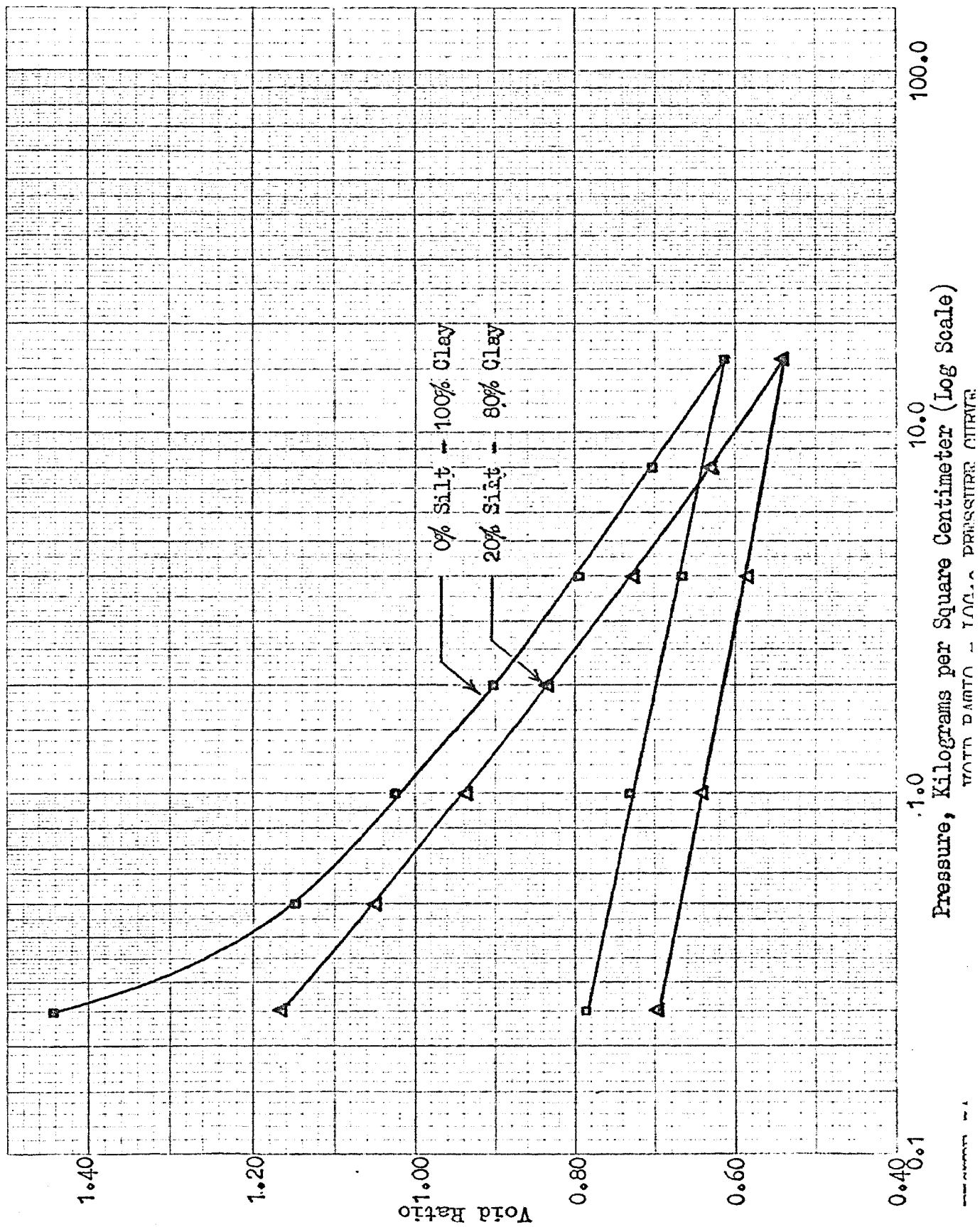
An exact analysis of coefficient of permeability (k) was not possible because of the difficulty in determining t_{90} and t_{100} for samples with high silt content. The coefficient of permeability values for samples of 0, 20 and 40 percent silt, within the virgin portion of the consolidation curve, averaged 0.015×10^{-4} , 0.025×10^{-4} and 0.045×10^{-4} centimeters per second respectively, throughout the various pressure increments. Values of the coefficient of permeability for the sample with 60 percent silt indicate a rather sharp rise to an average of approximately 0.225×10^{-4} centimeters per second. Samples of 70, 80 and 100 percent silt varied within the range of that of 60 percent silt to an average value of approximately 0.275×10^{-4} centimeters per second.

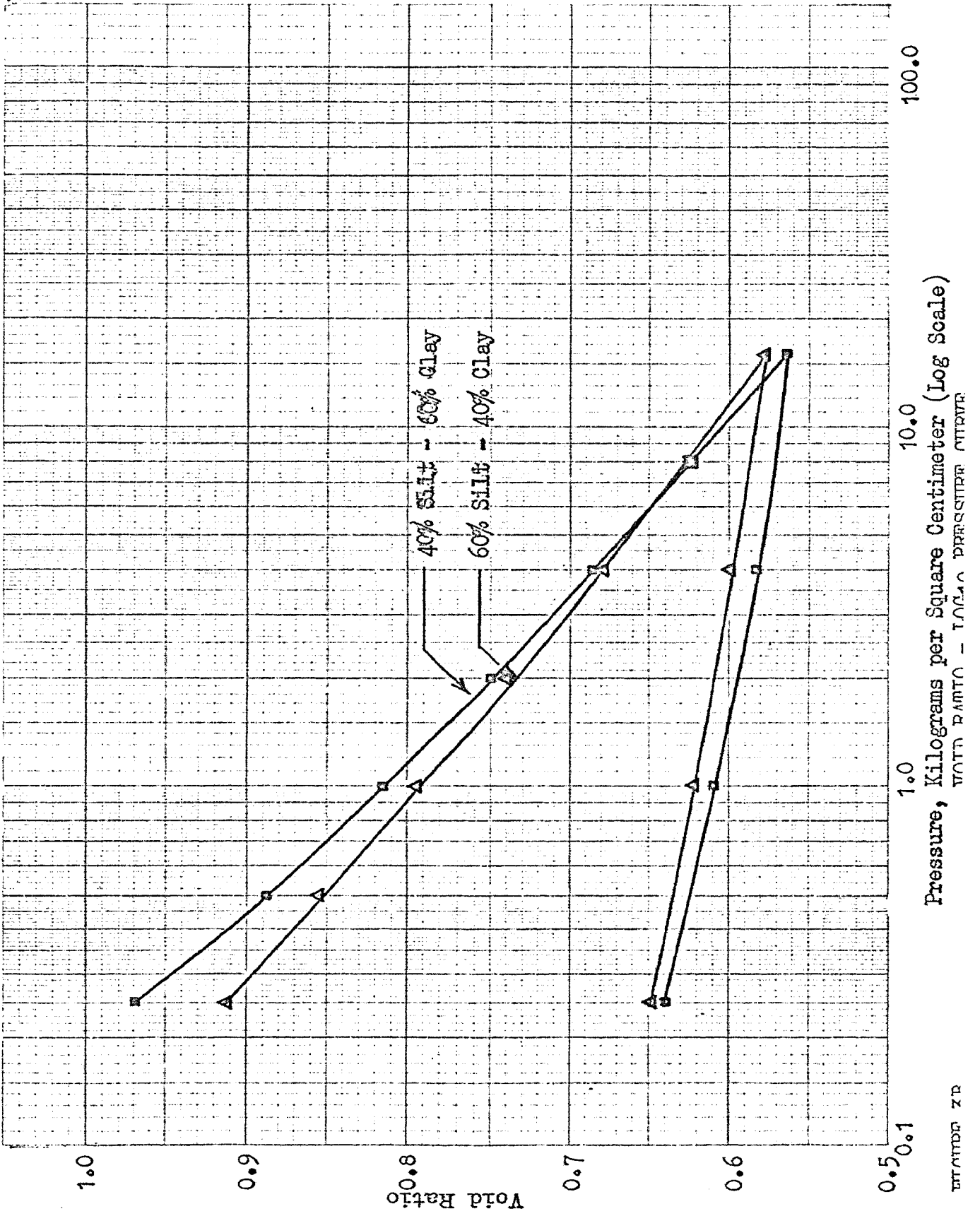
Comparison of void ratio versus \log_{10} pressure curves revealed several important factors on the behavior of clay with varying percentages of silt mixture. Compressibility of samples within each of the three groups is similar (Figs. 3A, 3B and 3C). The following table indicates pertinent properties of the various samples.

TABLE 1 - PROPERTIES OF COMPRESSIBILITY

Percent Silt	Initial Water Content	Final Water Content	Liquid Limit	Comperssion Index
0	57.2	30.2	56	0.408
20	52.1	28.2	45	0.307
40	41.2	25.1	35	0.210
60	36.7	25.6	29	0.174
70	35.4	28.6	27	0.115
80	33.4	31.0	25.6	0.082
100	33.9	33.8		0.0288

Comparison of virgin and rebound void ratio - \log_{10} pressure curves revealed that three distinct shapes of curves were present -- concave upward, concave downward and straight lines. Both virgin and rebound curves of samples with 0 percent through 60 percent silt are concave upward. Similarly, virgin and rebound curves of samples with 100 and 80 percent silt are concave downward. Curves of all groups tend to approach the plot of that sample whose mixture is 70 percent





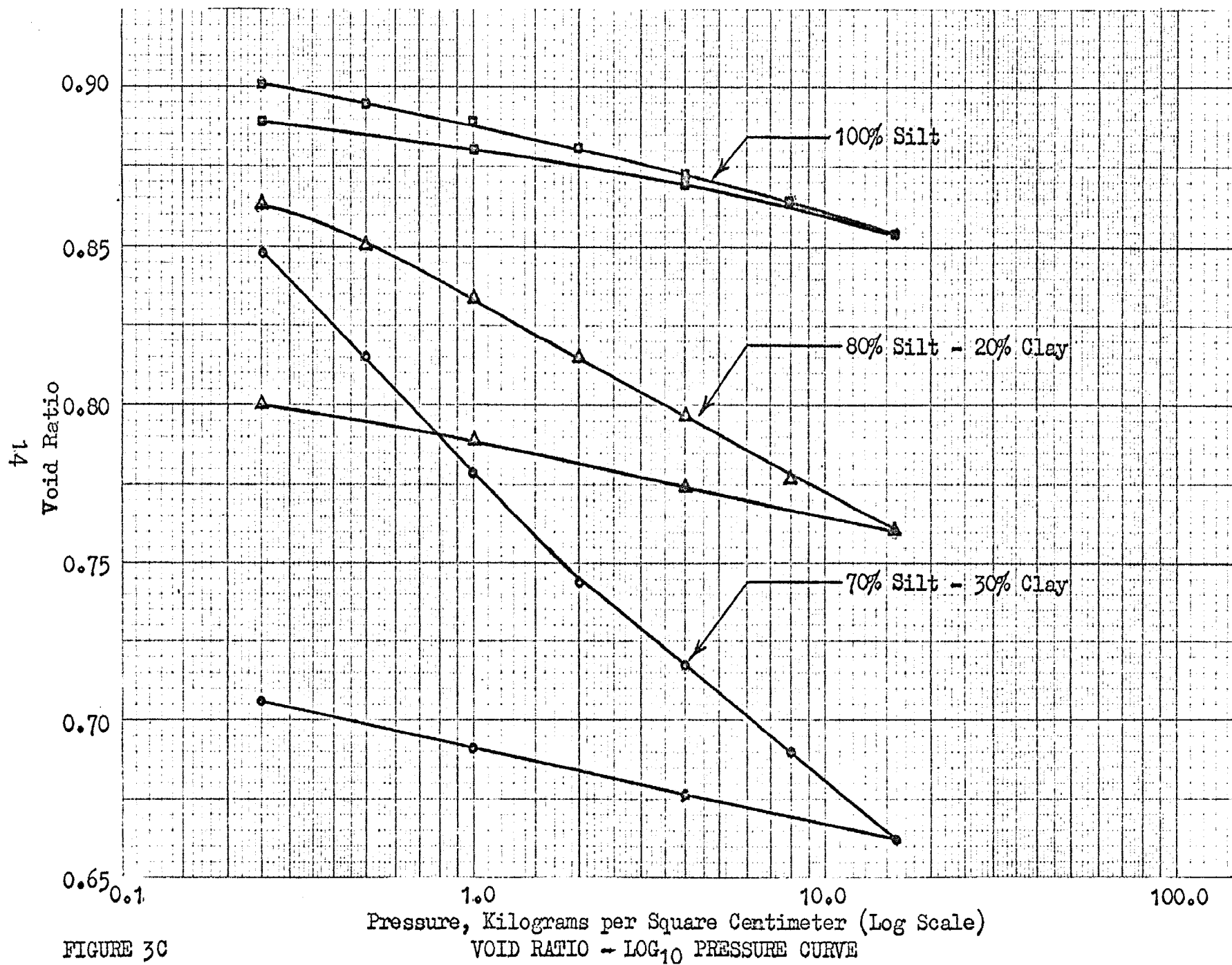


FIGURE 3C

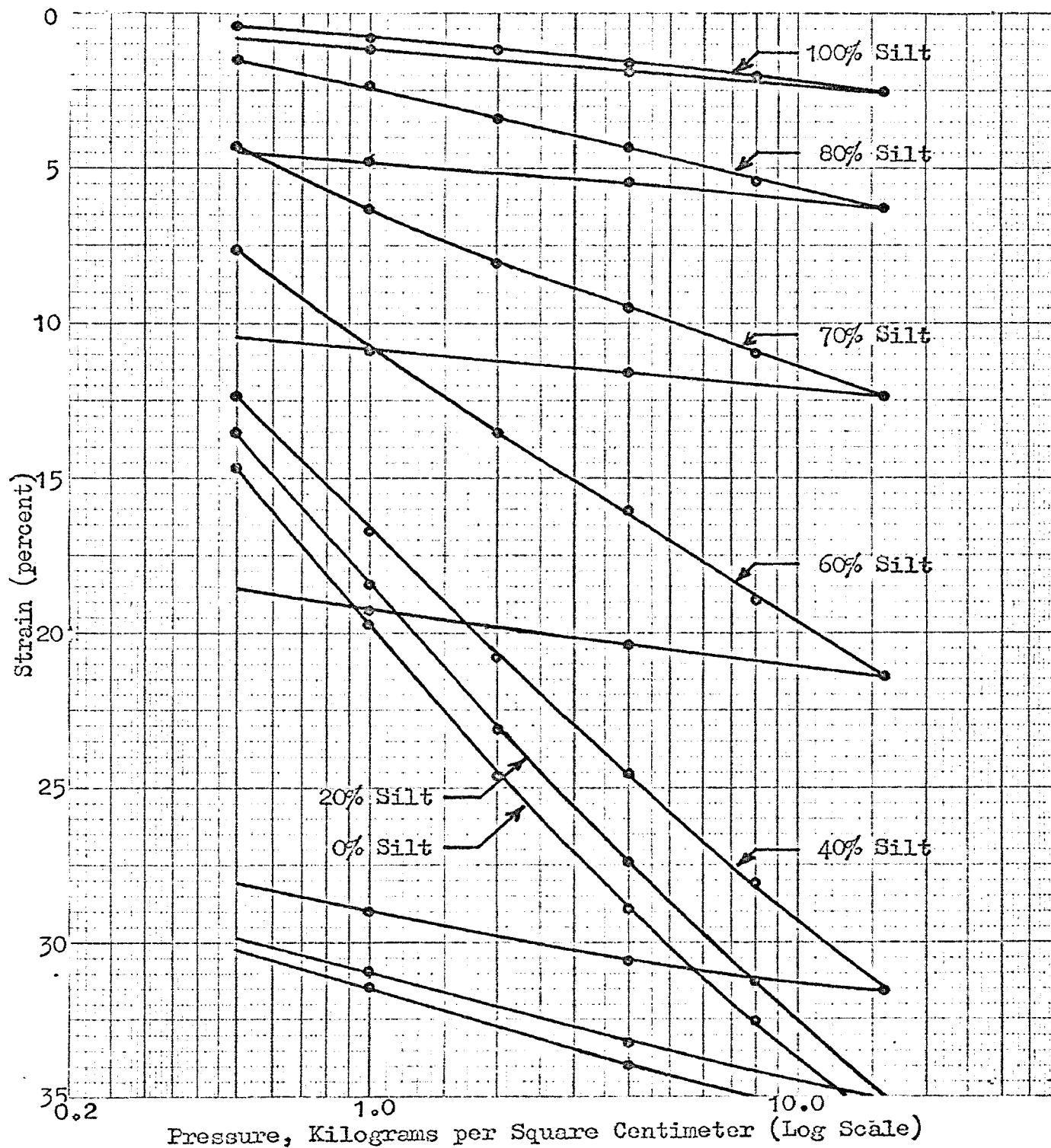
silt and 30 percent clay (Fig. 3C). This particular curve exhibits a straight line rebound curve. The virgin portion of the curve consists essentially of two straight line portions merging with a slight curvature at the 2 kilograms per square centimeter pressure increment. The shape of these curves appear to be indicators of the predominant influence of either the silt or clay on the behavior of the sample. An overall comparison of curve shapes can be more clearly observed by means of the strain - \log_{10} pressure plot of all samples (Fig. 4). The 1/4 kilogram per square centimeter pressure increment was omitted from the strain - \log_{10} pressure curves for clarity. It should be mentioned at this point that the structural breakdown previously discussed, is illustrated in the void ratio - \log_{10} pressure curve for 100 percent clay (Fig. 3A) which has the shape typical of a sensitive clay.

Comparison between the compression index values (C_c) and liquid limit values (L_w) reveals a departure from the empirical relationship that has been developed for normally loaded clays (Fig. 5). The lower continuous line (1) represents a plot of $L_w - C_c$ relationship computed by the basic equation⁷

$$C_c = 0.009(L_w - 10)$$

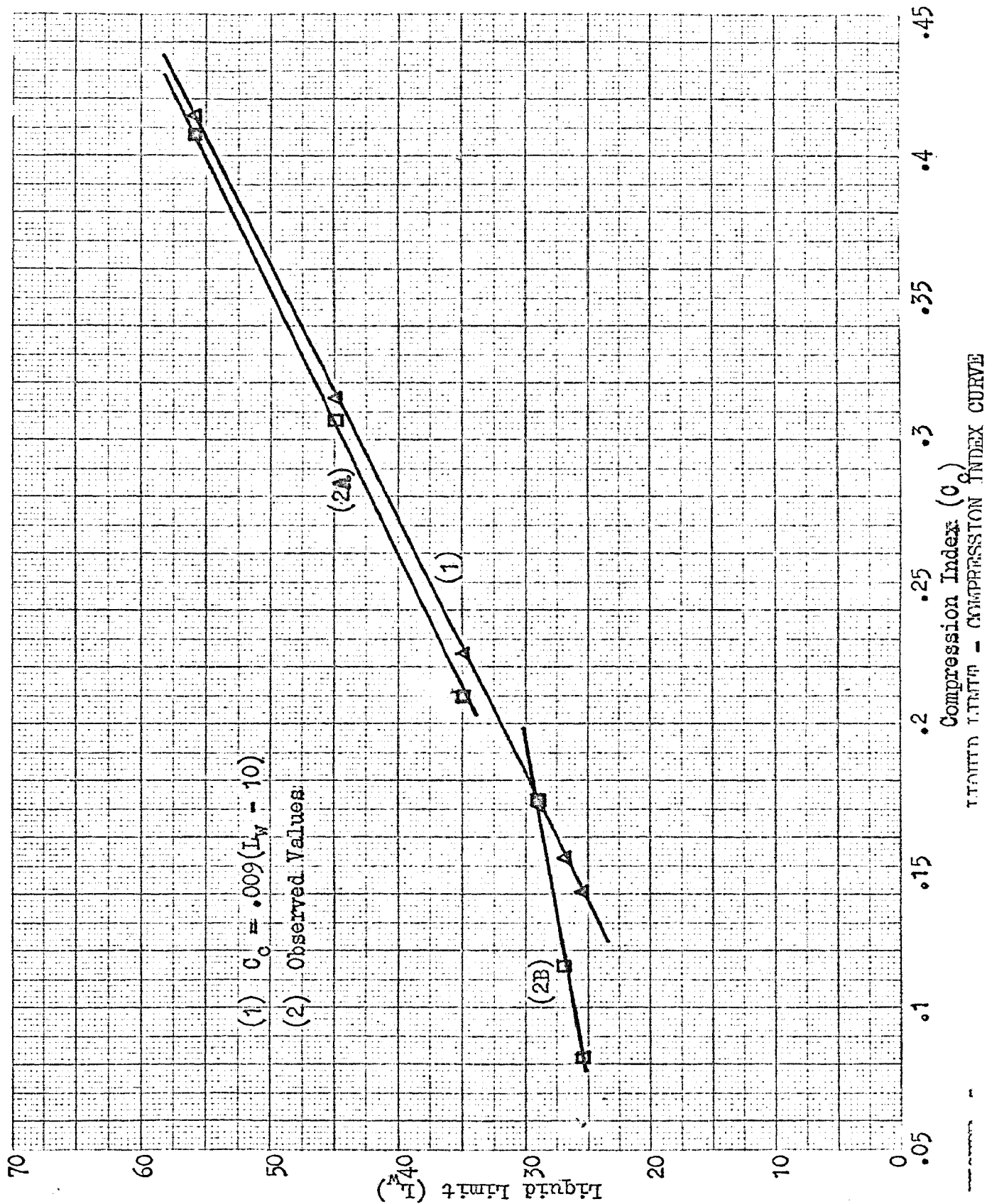
The data points indicated on line 1 represent the actual liquid limits of the samples and C_c as computed by the above equation. However, when C_c values were interpolated from the void ratio - \log_{10} pressure curves,

7. Skempton, A. W., "Notes on the Compressibility of Clays", Quart. J. Geol. Soc., London 1944



STRAIN - \log_{10} PRESSURE CURVE

FIGURE 4

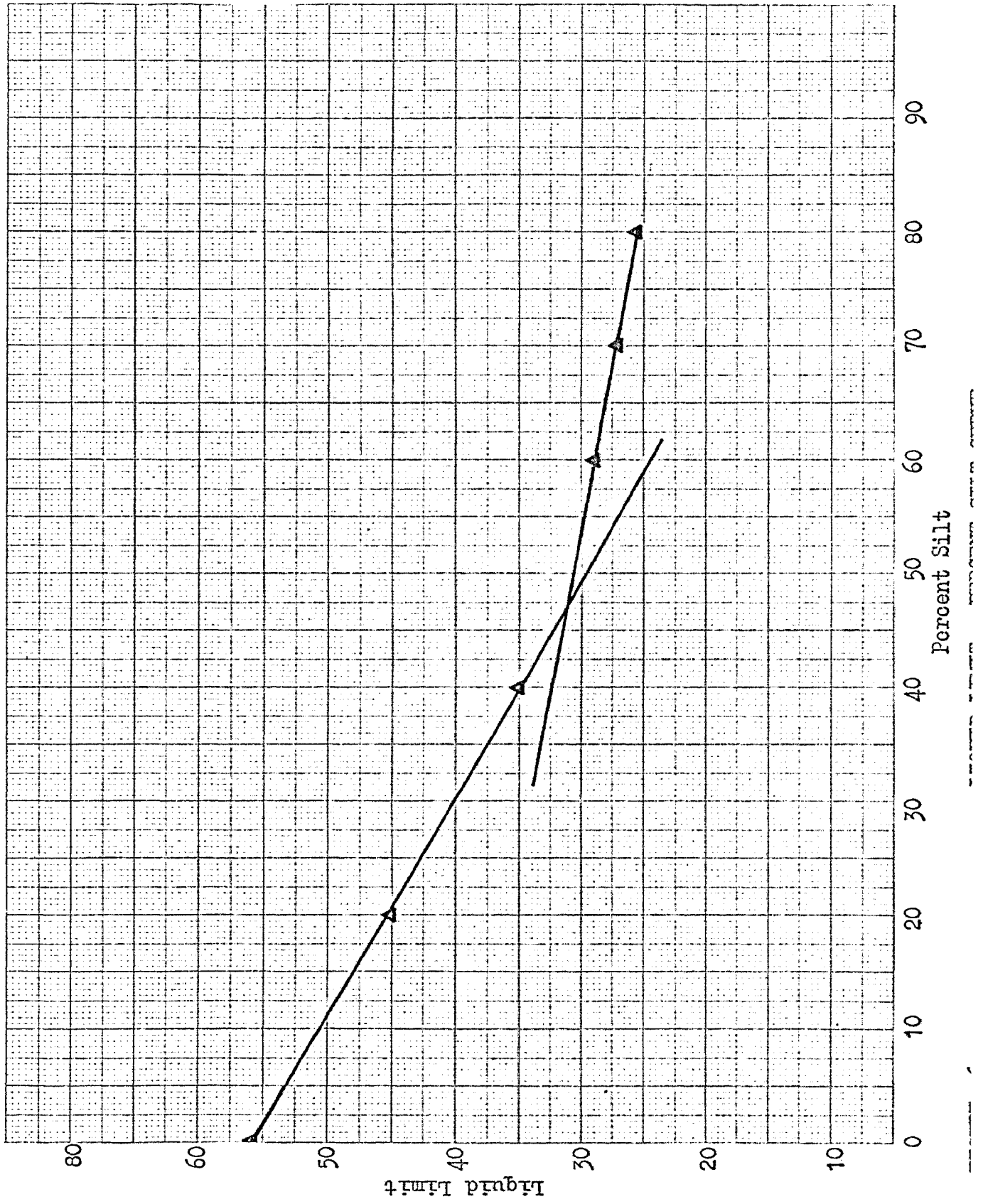


two different line segments were obtained, as indicated (2A and 2B). Line 2A represents samples of 0 to 40 percent silt and line 2B represents samples of 60 to 80 percent silt. The samples with lower percentages of silt (2A) closely approximate the plot from the basic equation previously mentioned. However the samples with high percentages of silt (2B) indicate a departure from normal expectation. It also tends to imply that soil samples with silt percentages between 40 and 60 exhibit a departure in fundamental behavior in consolidation tests.

A comparison of percent silt with liquid limit also illustrates an abrupt change in action from clay to silt (Fig. 6). This curve indicates a change at a liquid limit of approximately 31 and a sample mixture of about 47 percent silt and 53 percent clay. These values tend to agree with the results of the consolidation tests plotted in figure 5.

It should be noted that in the figures shown in which liquid limits or water contents are plotted, values for samples of 100 percent silt are omitted. These test values are only approximate because of the difficulty that was experienced in removing excess surface water from the sample without disturbing the actual water content.

The relationship between compression index and silt-clay content values indicates a nearly straight line.. Although some scatter of points is evident, it should be noted that in the high silt content range, the observed points closely agree with the indicated proportionality (Fig. 7).



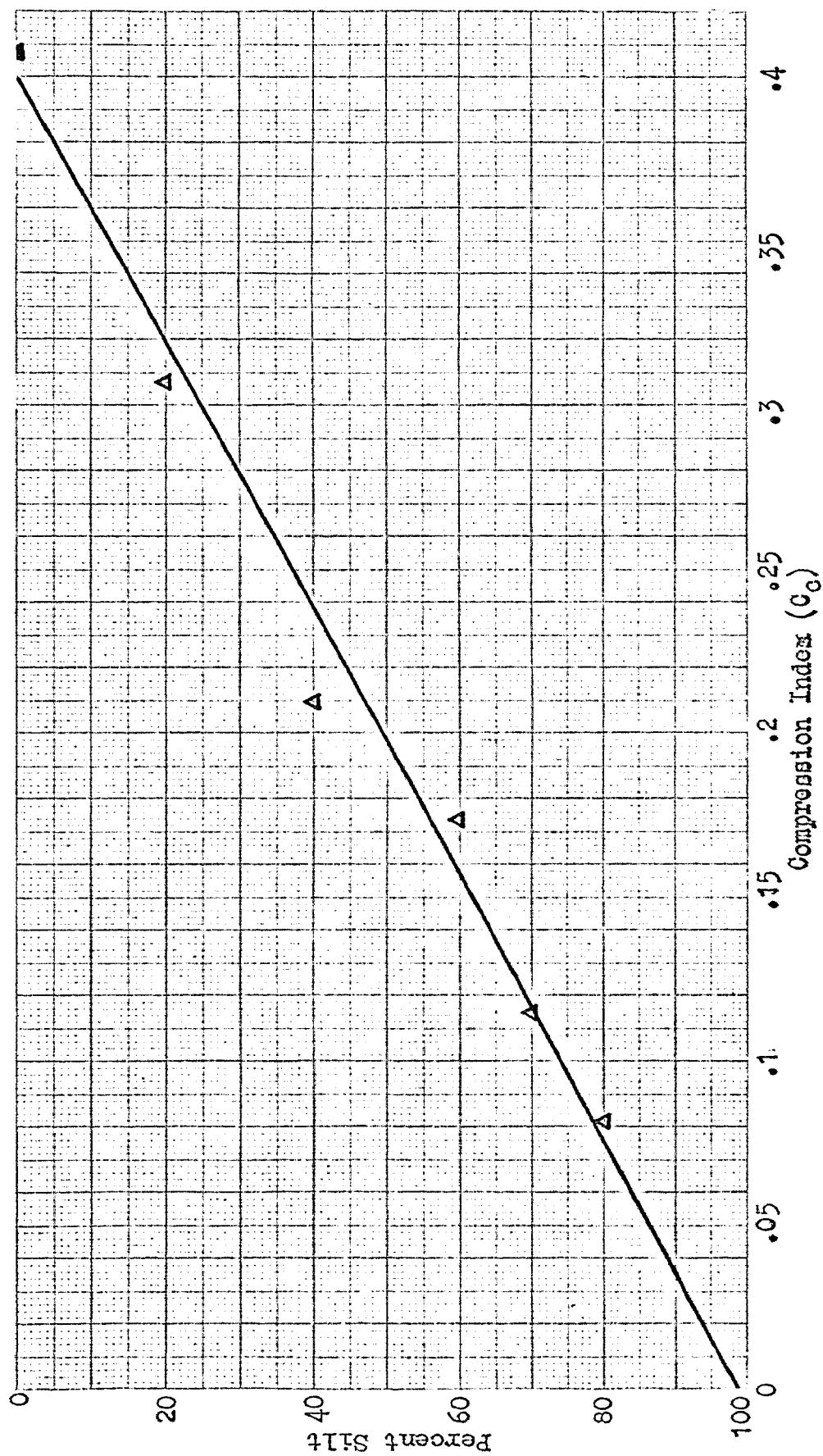


FIGURE 7 PERCENT SILT - COMPRESSION INDEX CURVE

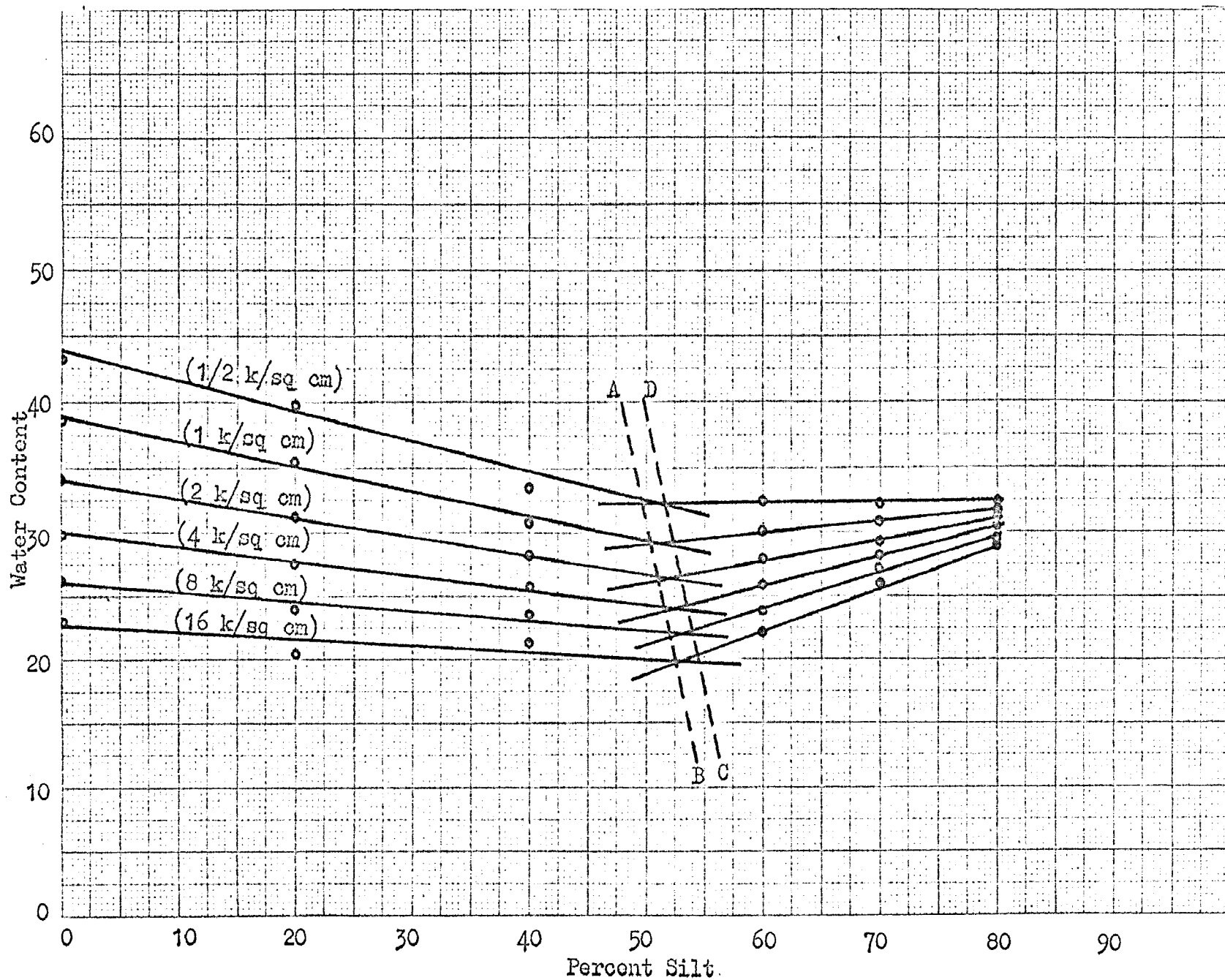
Comparison of water contents of the various samples, under the different load increments during testing, to the percent silt present in each sample, reveals the family of curves illustrated in figure 8. The sharp change in action from clay to silt, as previously mentioned, is further verified in this graph. A connection of the points of intersection of the straight lines shown, delineates the area ABCD. If the ordinate and abscissa were interchanged, the area ABCD could be seen to have the same slope as the plot of C_c versus percent silt (Fig. 7).

It may be observed that the data points indicate curved lines, rather than straight ones, for those to the left of area ABCD. It is suggested that the location of area ABCD would remain evident, if curved lines were used, because of the configuration of the curves required to fit the data.

Although the method of determination of area ABCD may be questioned, it is suggested that the area obtained allows for reasonable prediction of the slope of the C_c versus percent silt proportionality, within tolerable limits.

CONCLUSIONS

Results of this study lead to several conclusions pertaining to the effect of the silt content on the compressibility of cohesive soil mixtures.



With respect to sensitivity, or structural change during consolidation from a normally loaded condition, the presence of merely 20 percent silt almost negates any evidence of this occurrence in the void ratio - \log_{10} pressure curve, even though it remains apparent in the dial reading - \log_{10} time curves. This indicates that any loose structure which occurs is counteracted by silt particles and that the magnitude of consolidation decreases with the increasing percentages of silt.

The maximum primary consolidation time of clay is greatly affected by the addition of small amounts of silt. From a 100 percent clay condition the maximum primary consolidation time is decreased nearly 4 times by merely adding 20 percent silt to the sample. Added amounts of silt above 20 percent will decrease this time to approximately 15 percent of the original 100 percent clay consolidation time. Consequently, it is evident that small variations of silt continuity in clay deposits may drastically vary consolidation times.

The compressibility of clay samples tend to decrease directly with the amount of silt present. This is particularly true in mixtures with high silt contents as shown in figure 7. By addition of 60 percent silt, the decrease in compressibility will be nearly $1/2$, and the addition of 70 percent silt will cause a decrease in the compressibility of the clay by $2/3$. It may be surmised, therefore, that prediction of settlement and consolidation of normally loaded silt-clay deposits, with liquid limits less than 50 percent, may be quite conservative if

the calculations are based on current empirical methods. It is obvious from figure 5 that the basic equation for determining C_c in clay materials may introduce excessive error for materials with high silt contents. For predominately silty soils other relationships must be used for accurate prediction of settlement. This may provide partial explanation for the fact that consolidation observed in the field is always less than that which is predicted in the laboratory. Utilization of the relationship between percent silt, water content, existing pressure and C_c , as presented in this study, in conjunction with other known properties of a given soil deposit, may be one possible method of more accurately predicting settlements for silty soils, when in the saturated, normally loaded condition.

The permeability of silt-clay mixtures varies over a rather wide range, with the division of silt action versus clay action existing at approximately 50 percent mixture, as would normally be expected.

Considering the question, "At what point does a silty clay become a clayey silt, in relation to consolidation or compressibility?" initial indications from observation of the void ratio - \log_{10} pressure curves indicate the division occurs at a mixture of approximately 30 percent clay and 70 percent silt. However, analysis of liquid limits, water contents and compression index values indicate that the division occurs at a sample mixture of approximately 47 percent silt and 53 percent clay. It is suggested that for settlement analysis, the latter

of the two percentages of silt mentioned should be considered as the transition mixture between silty and clayey materials.

It should be noted that conclusions drawn are limited to the actions of the materials used and that a variation of soil types could easily lead to different results. However, it is expected that most common clays with silt mixtures would exhibit the same general characteristics as those developed in this study.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. Thomas S. Fry for his valued advice and guidance throughout their association, and particularly in relation to this study. The author also wishes to thank Dr. Norbert O. Schmidt for his many helpful suggestions during this investigation.

A particular appreciation is expressed to the author's wife and family whose continued encouragement contributed immensely to the completion of this project.

VITA

James Inman Spencer was born on July 12, 1939, in Statesville, North Carolina. Being the son of a United States Army Officer, he obtained his primary and secondary education at many schools throughout the United States, Europe and Japan. He graduated from The Citadel in Charleston, South Carolina, in 1961, with a Bachelor of Science in Civil Engineering degree, and entered directly into military service as a Regular Officer in the United States Army Corps of Engineers.

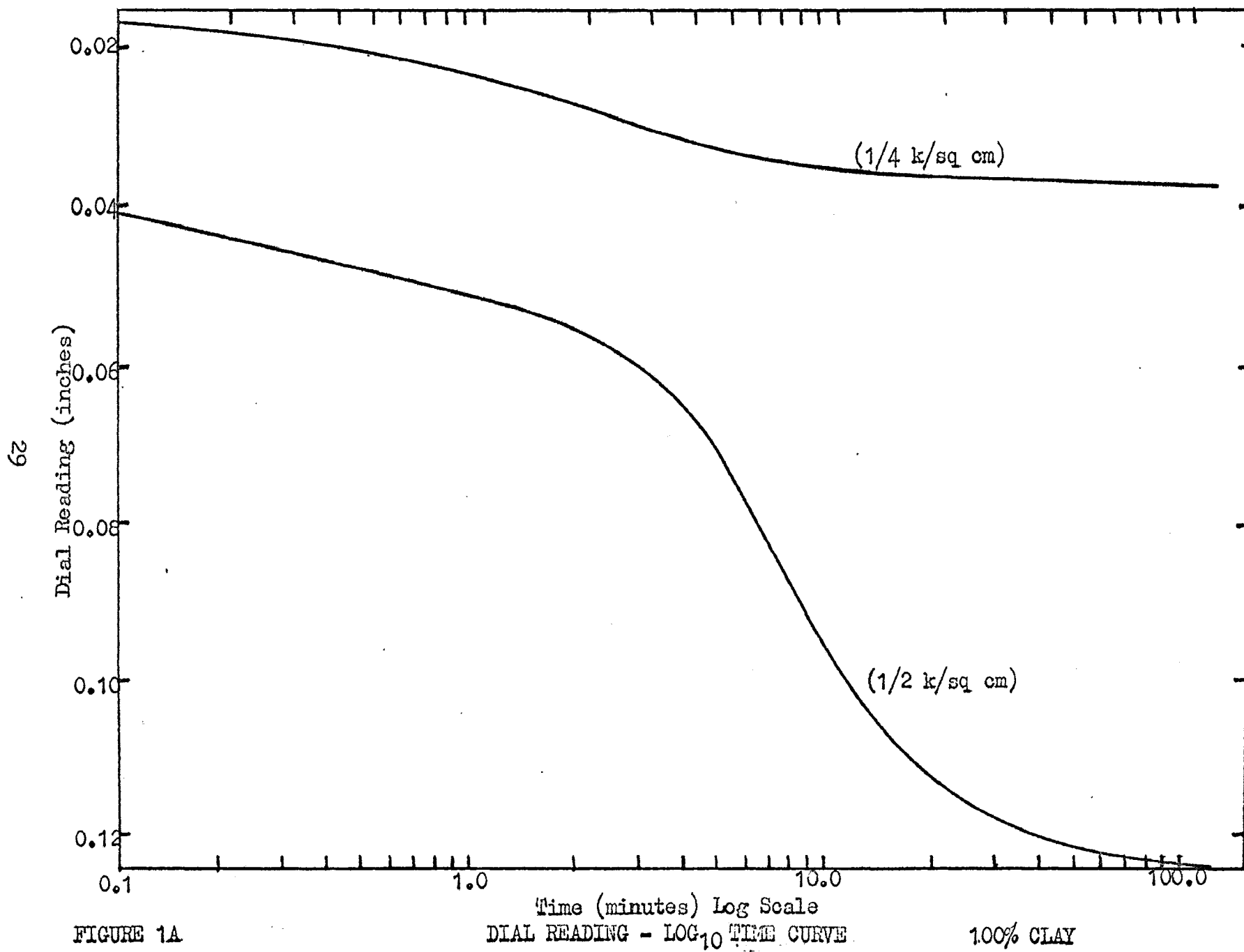
He was enrolled in the Graduate School of the University of Missouri at Rolla in January 1966, and received a Master of Science in Civil Engineering degree in May 1968.

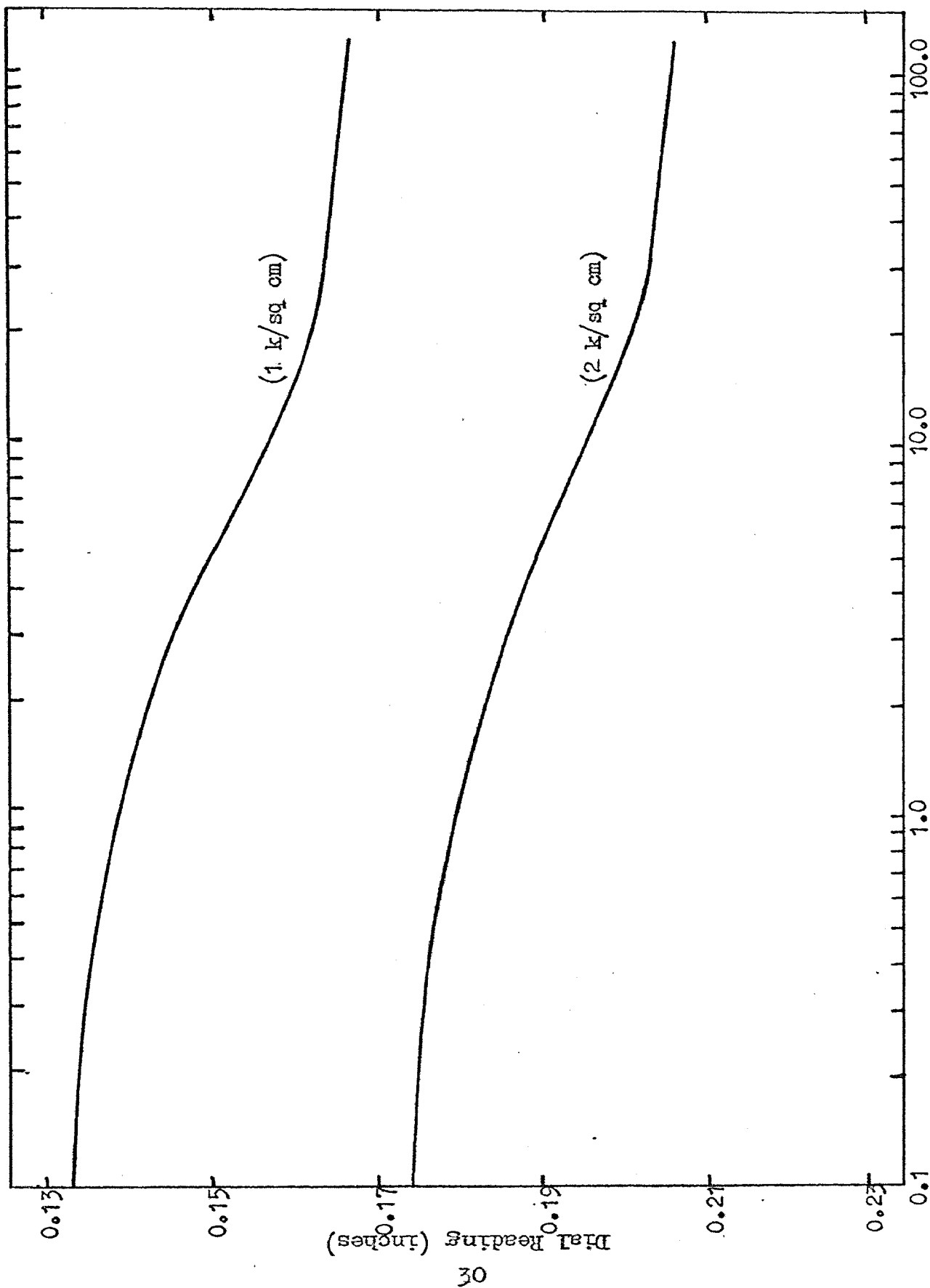
The author is married to the former Susan Beery and has two sons, James Inman Jr. and Charles Allen.

APPENDIX

Dial Reading - \log_{10} Time Curves

(Plots of actual test values)





Time (minutes) Log Scale

NOT AT DEPARTING - TAC MILES APPROX

100% N/A

INTERVAL 4.0

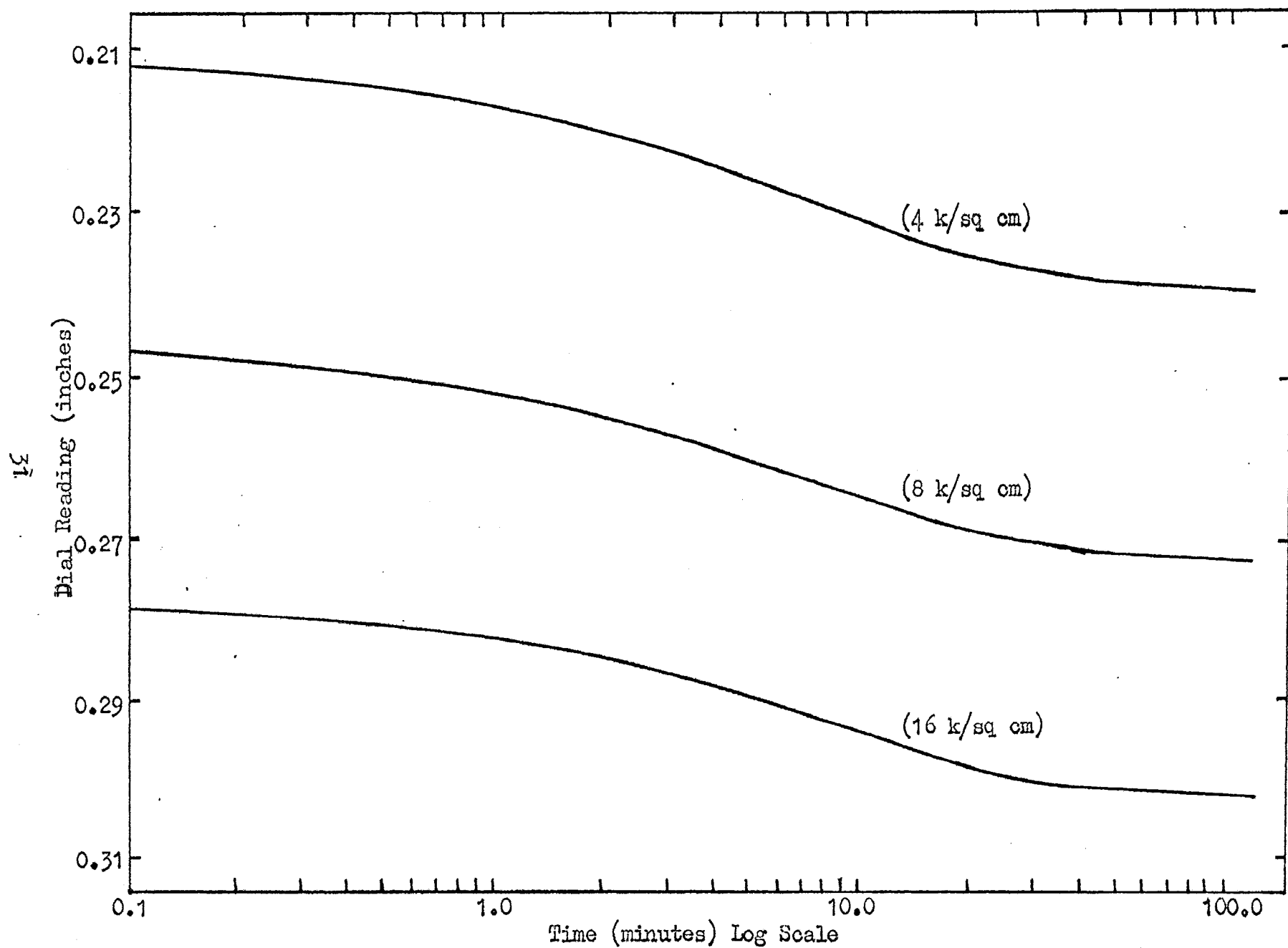


FIGURE 10

Time (minutes) Log Scale
DIAL READING - \log_{10} TIME CURVE

100% CLAY

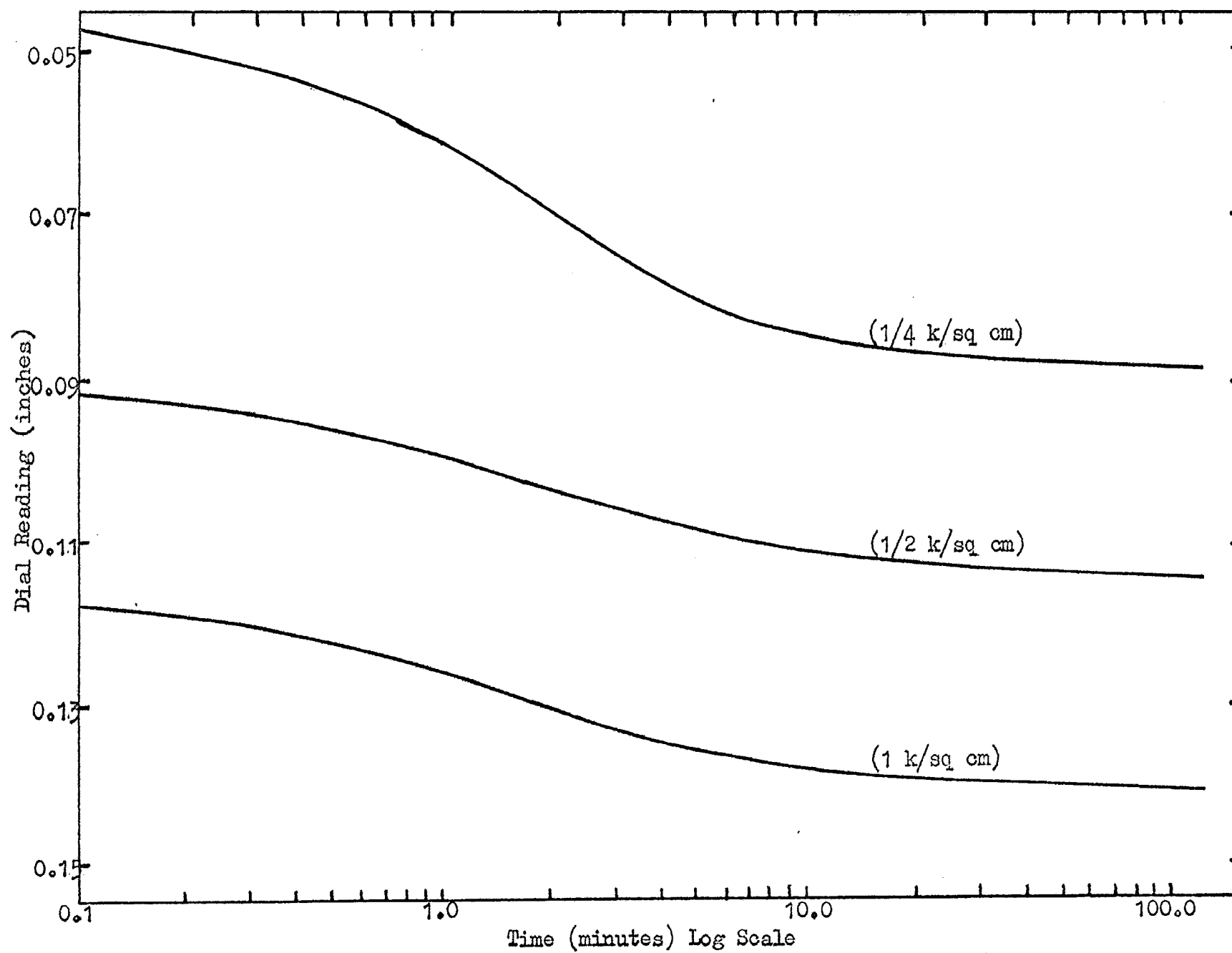


FIGURE 2A.

Time (minutes) Log Scale
DIAL READING - \log_{10} TIME CURVE

20% SILT - 80% CLAY

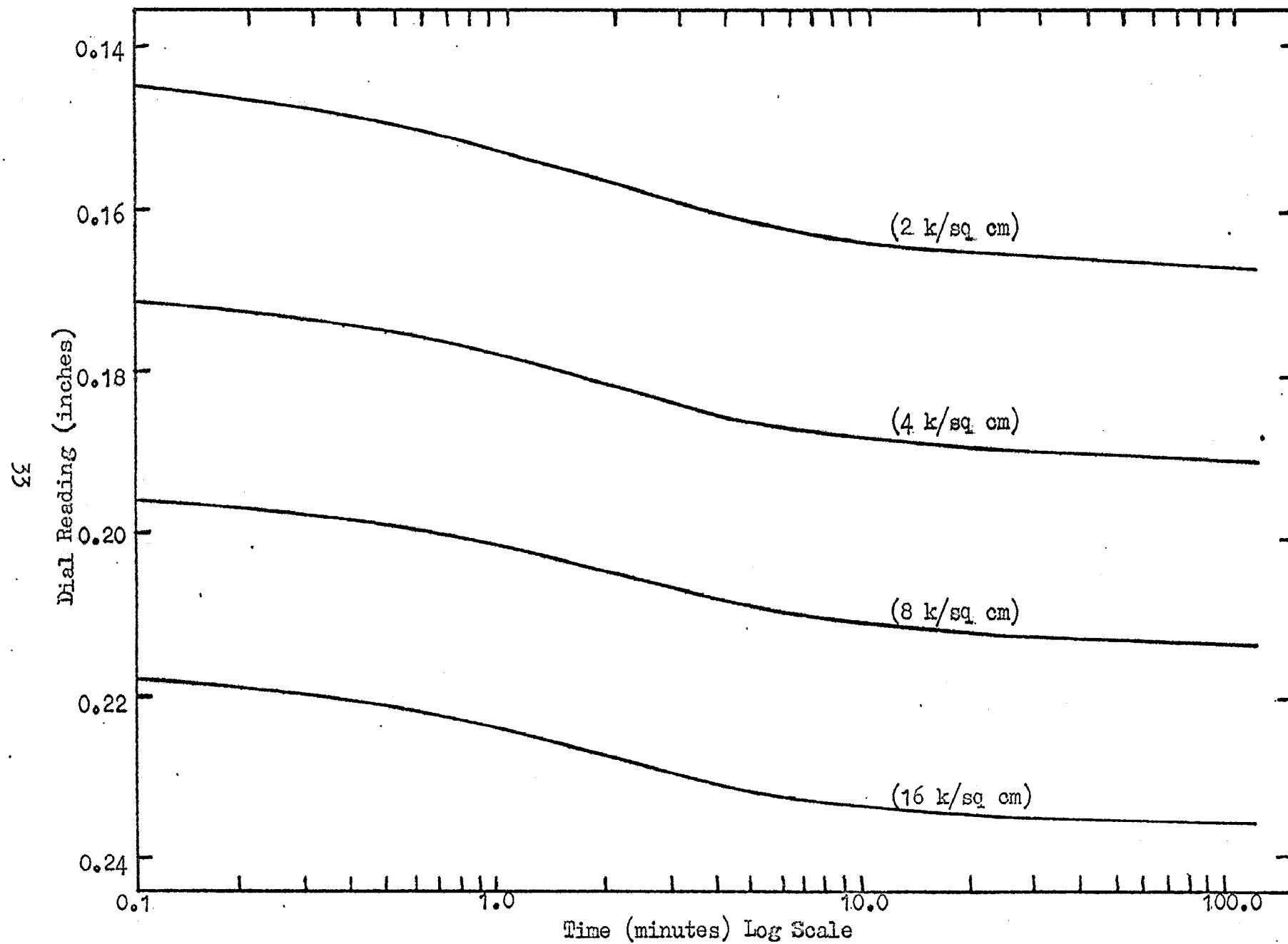


FIGURE 2B:

Time (minutes) Log Scale
DIAL READING - \log_{10} TIME CURVE

20% SILT - 80% CLAY

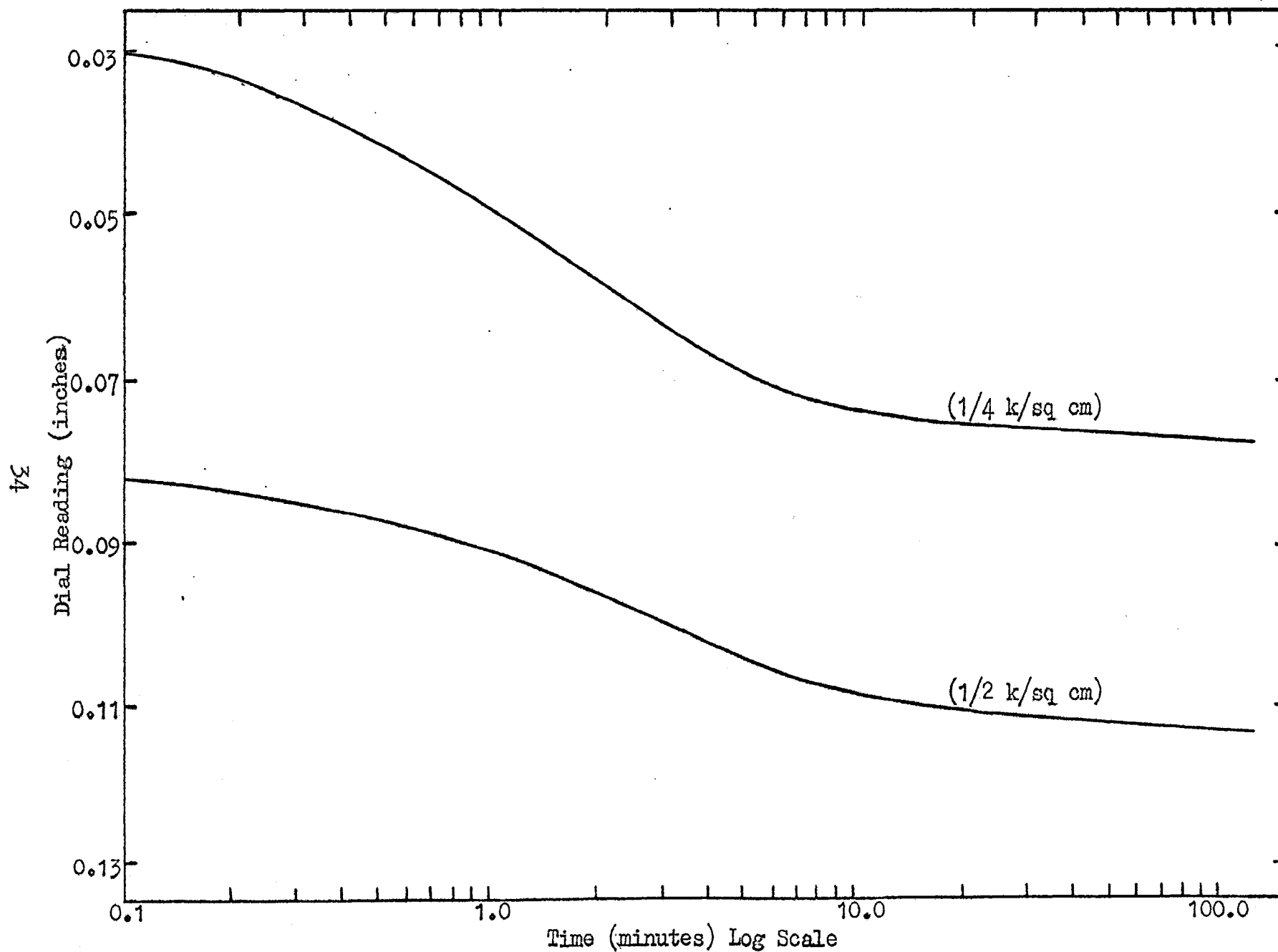


FIGURE 3A

Time (minutes) Log Scale
DIAL READING - LOG_{10} TIME CURVE

40% SILT - 60% CLAY

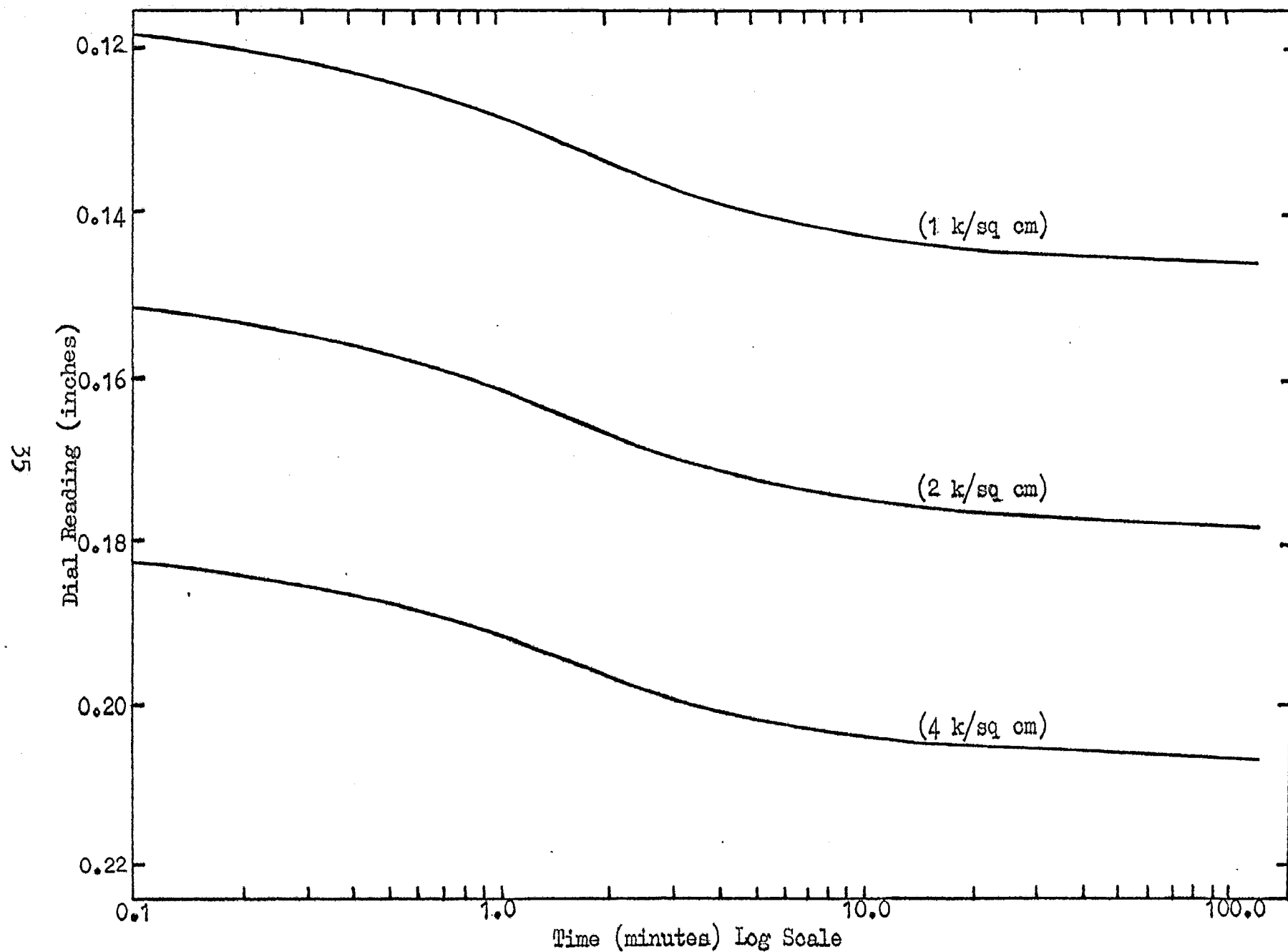


FIGURE 3B

DIAL READING - \log_{10} TIME CURVE

40% SILT - 60% CLAY

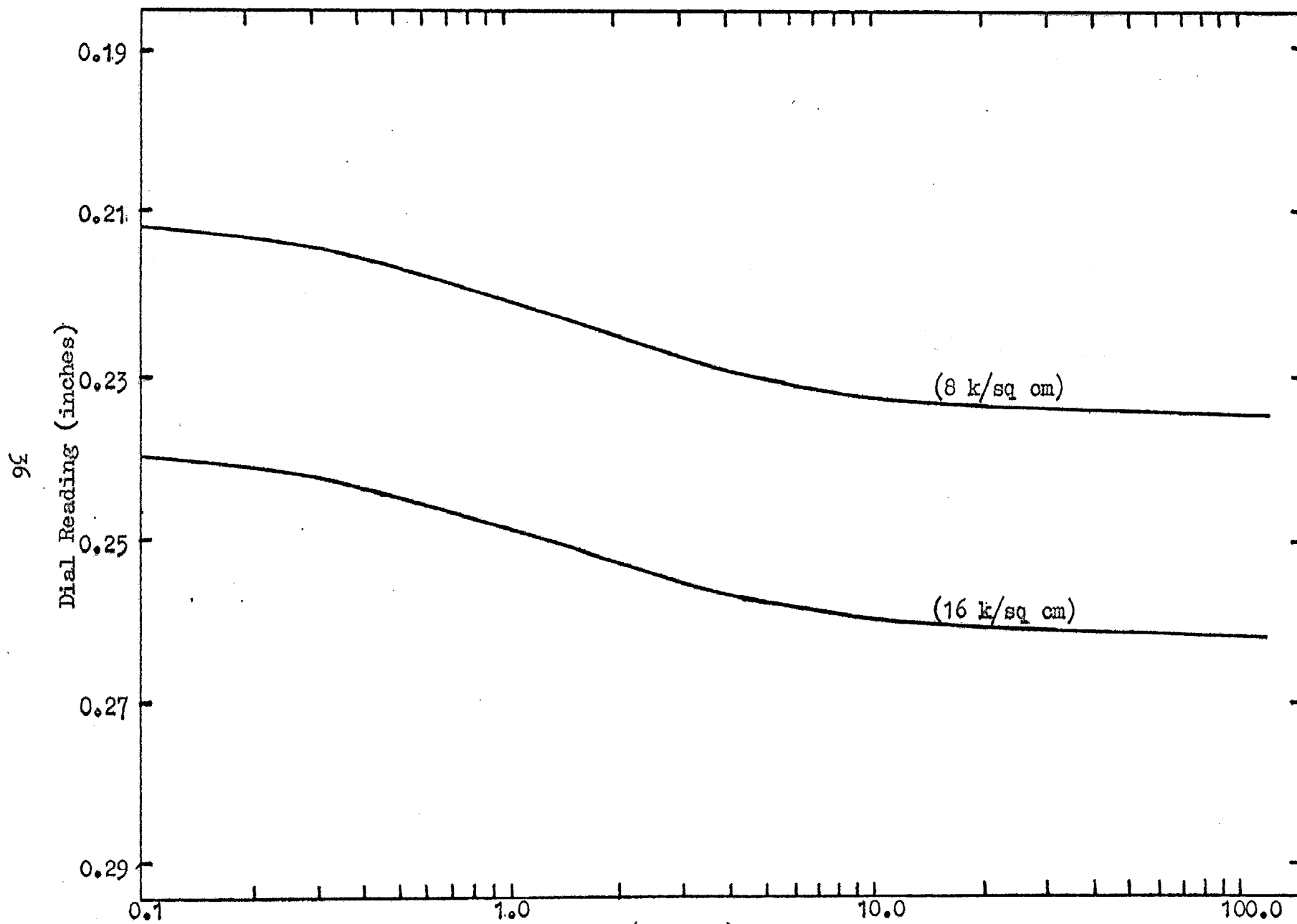


FIGURE 3C

DIAL READING - LOG_{10} TIME CURVE

40% SILT - 60% CLAY

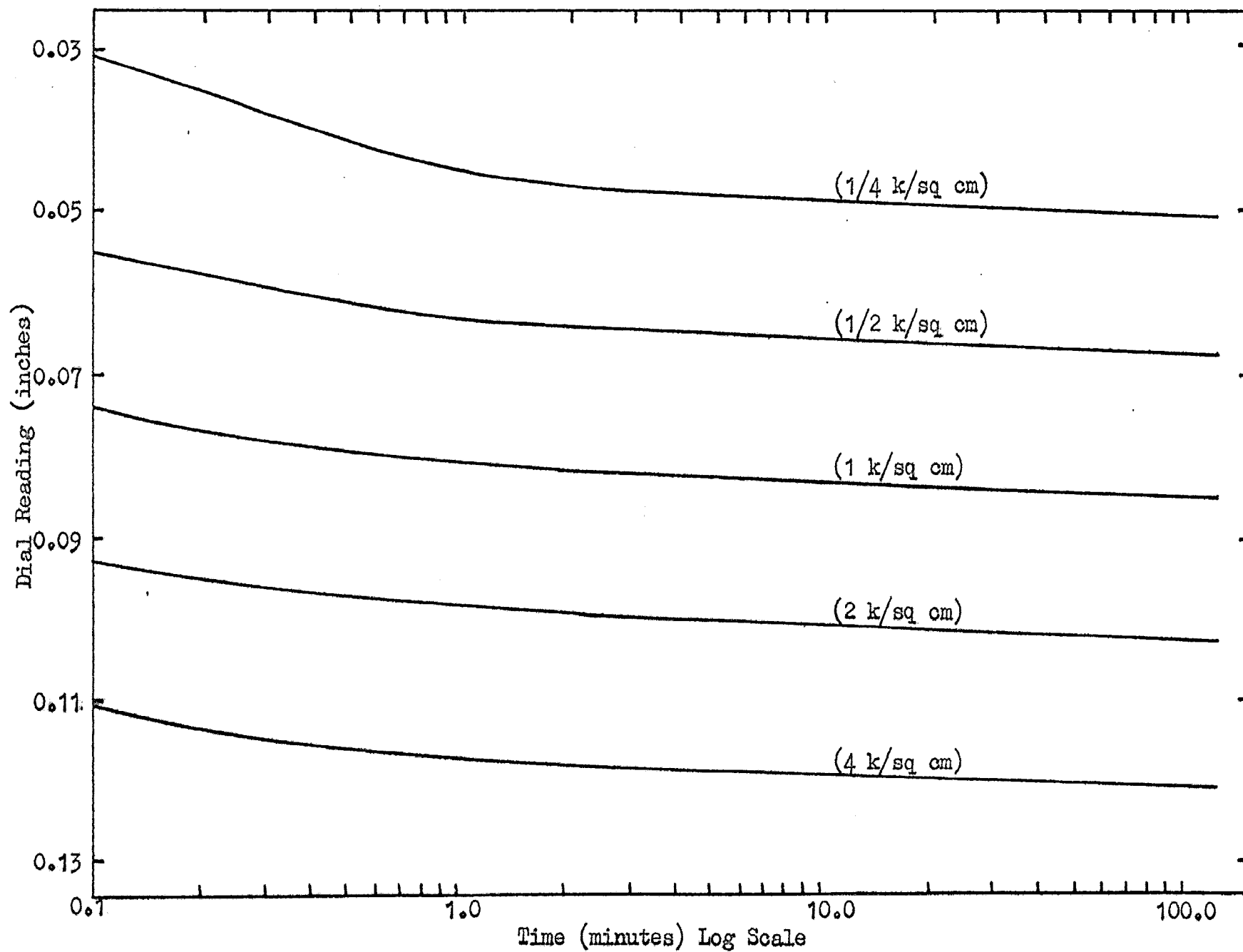


FIGURE 4A.

DIAL READING - \log_{10} TIME CURVE

60% SILT - 40% CLAY

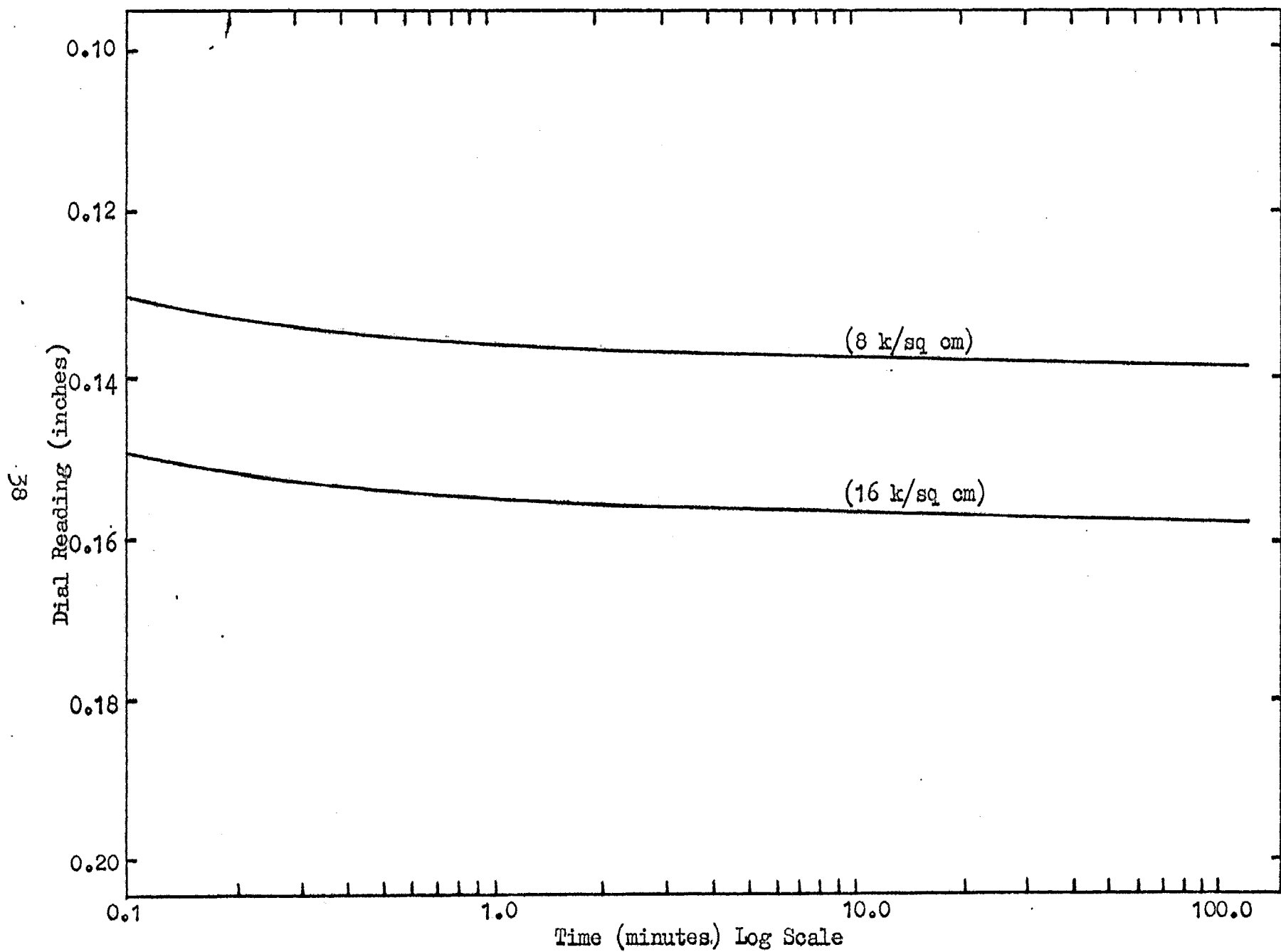


FIGURE 4B

Time (minutes) Log Scale
DIAL READING - LOG_{10} TIME CURVE

60% SILT - 40% CLAY

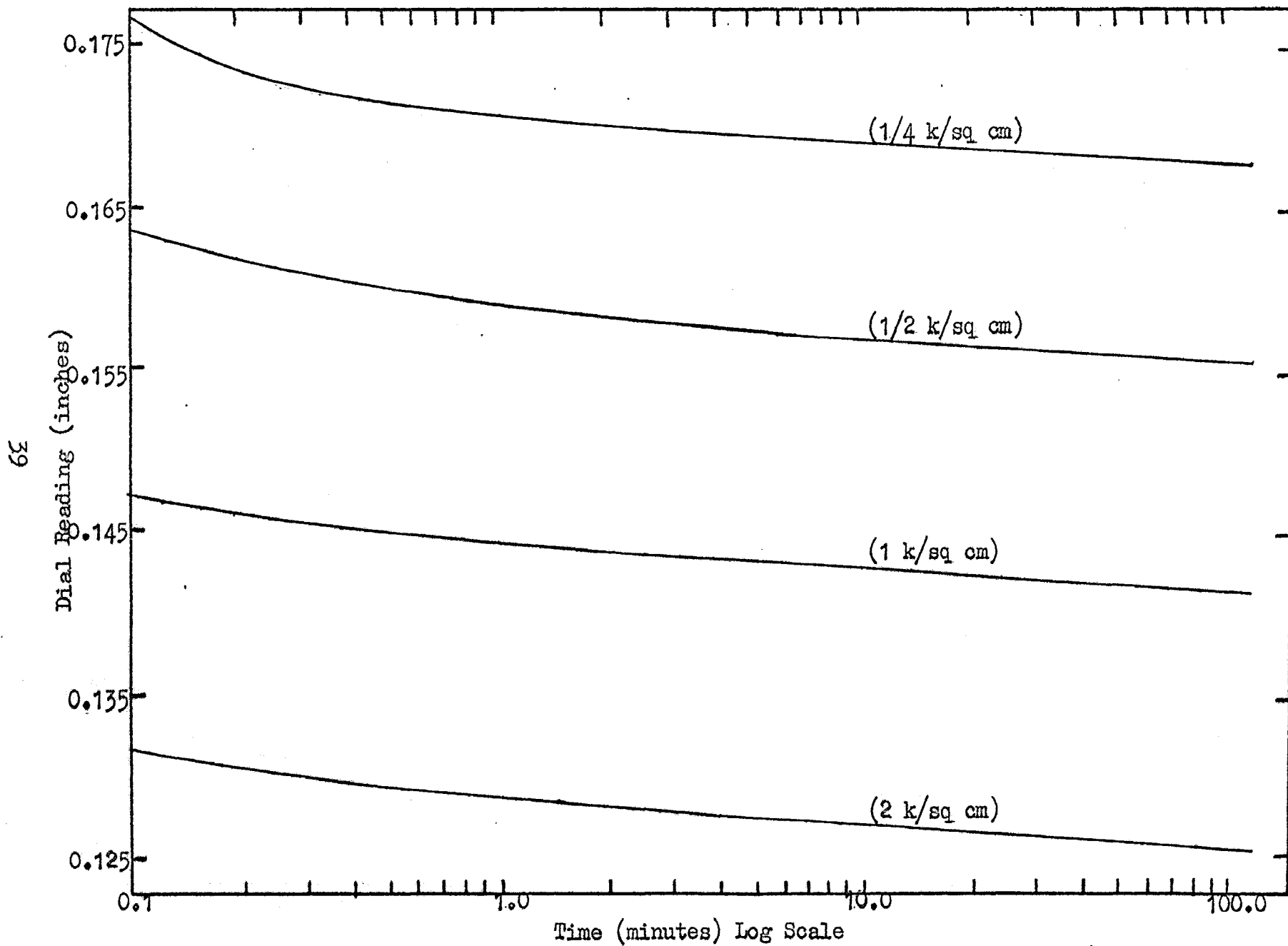


FIGURE 5A

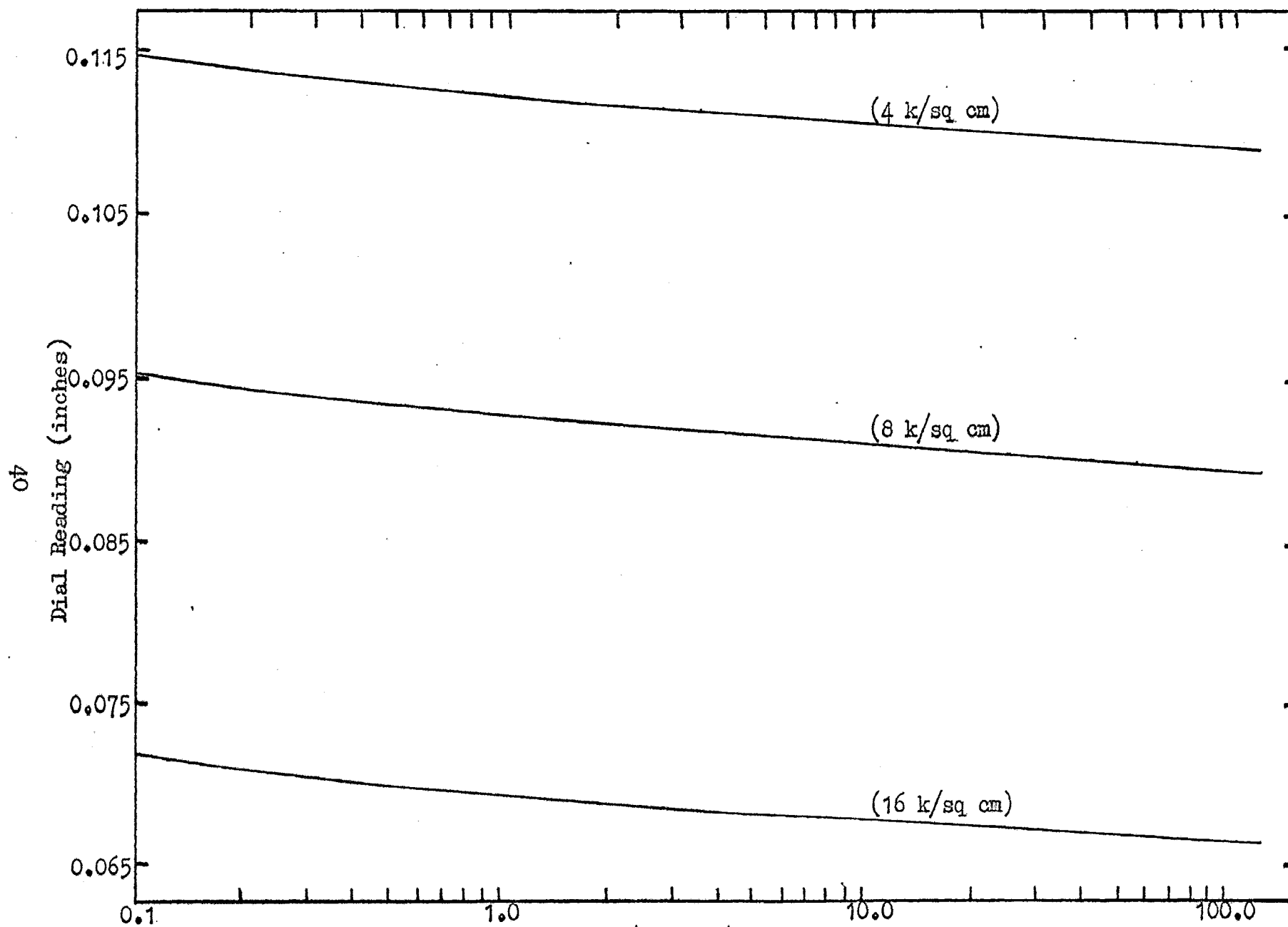


FIGURE 5B

Time (minutes) Log Scale
DIAL READING - \log_{10} TIME CURVE

70% SILT - 30% CLAY

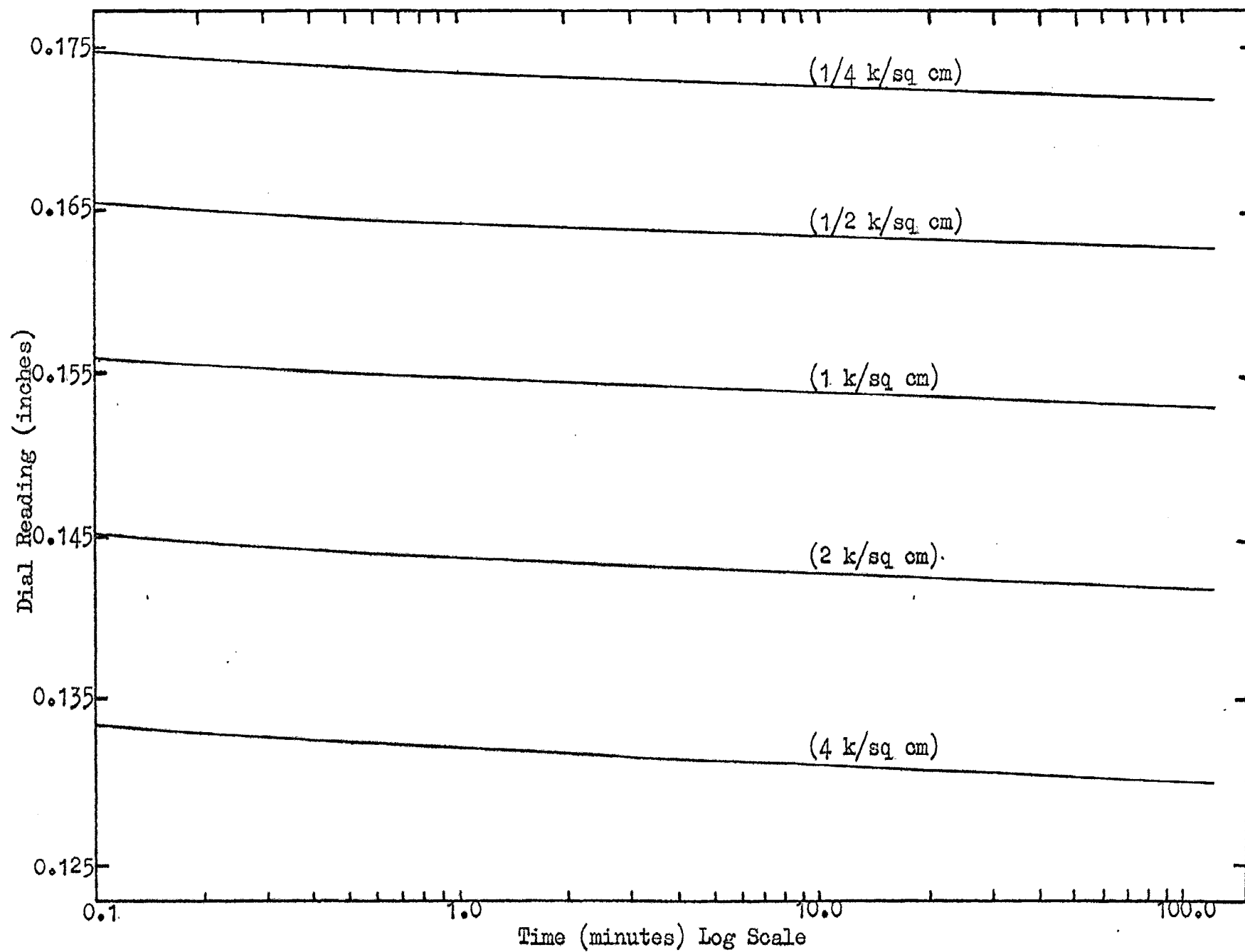


FIGURE 6A

Time (minutes) Log Scale
DIAL READING - LOG_{10} TIME CURVE

80% SILT - 20% CLAY

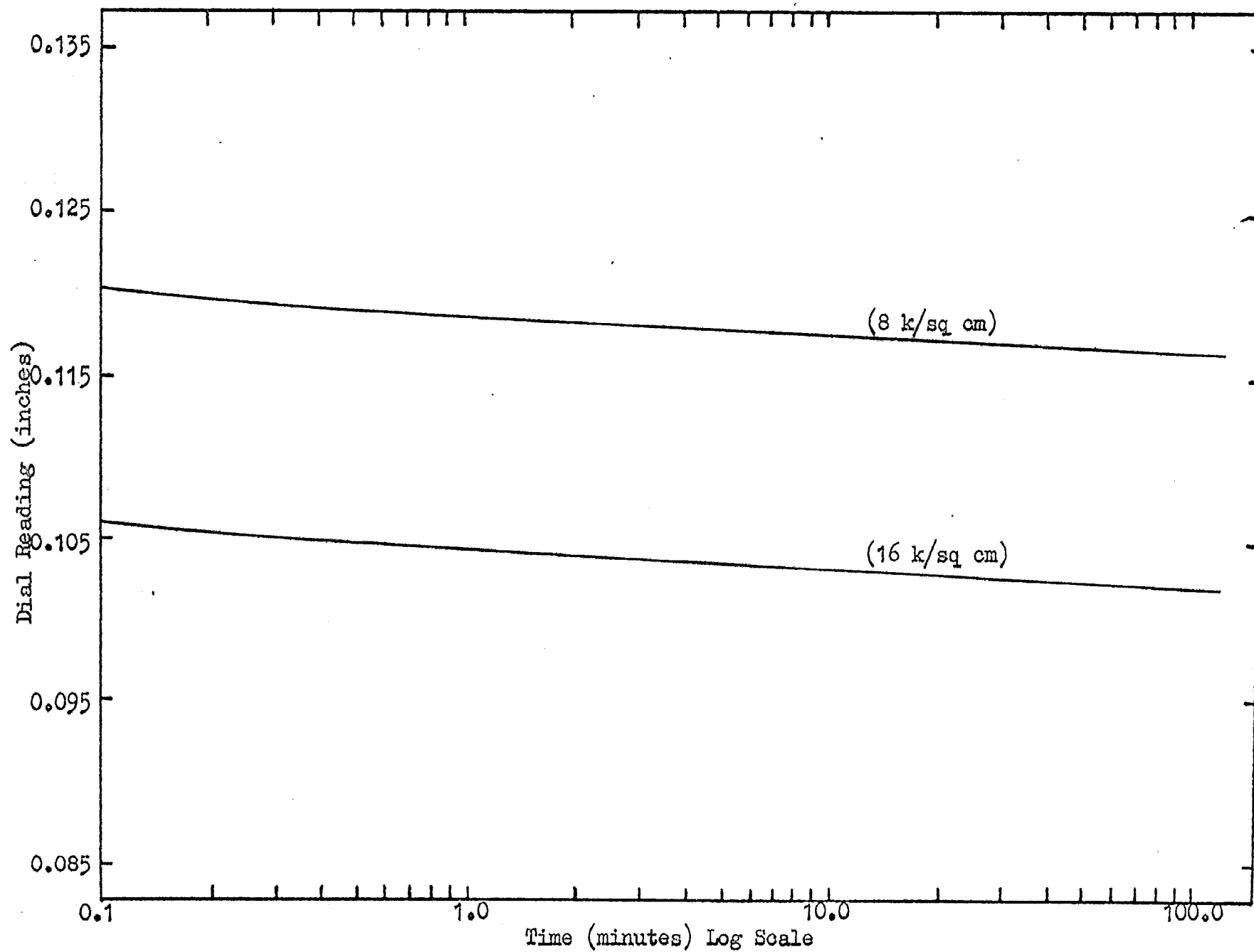


FIGURE 6B

Time (minutes) Log Scale
DIAL READING - \log_{10} TIME CURVE

80% SILT - 20% CLAY

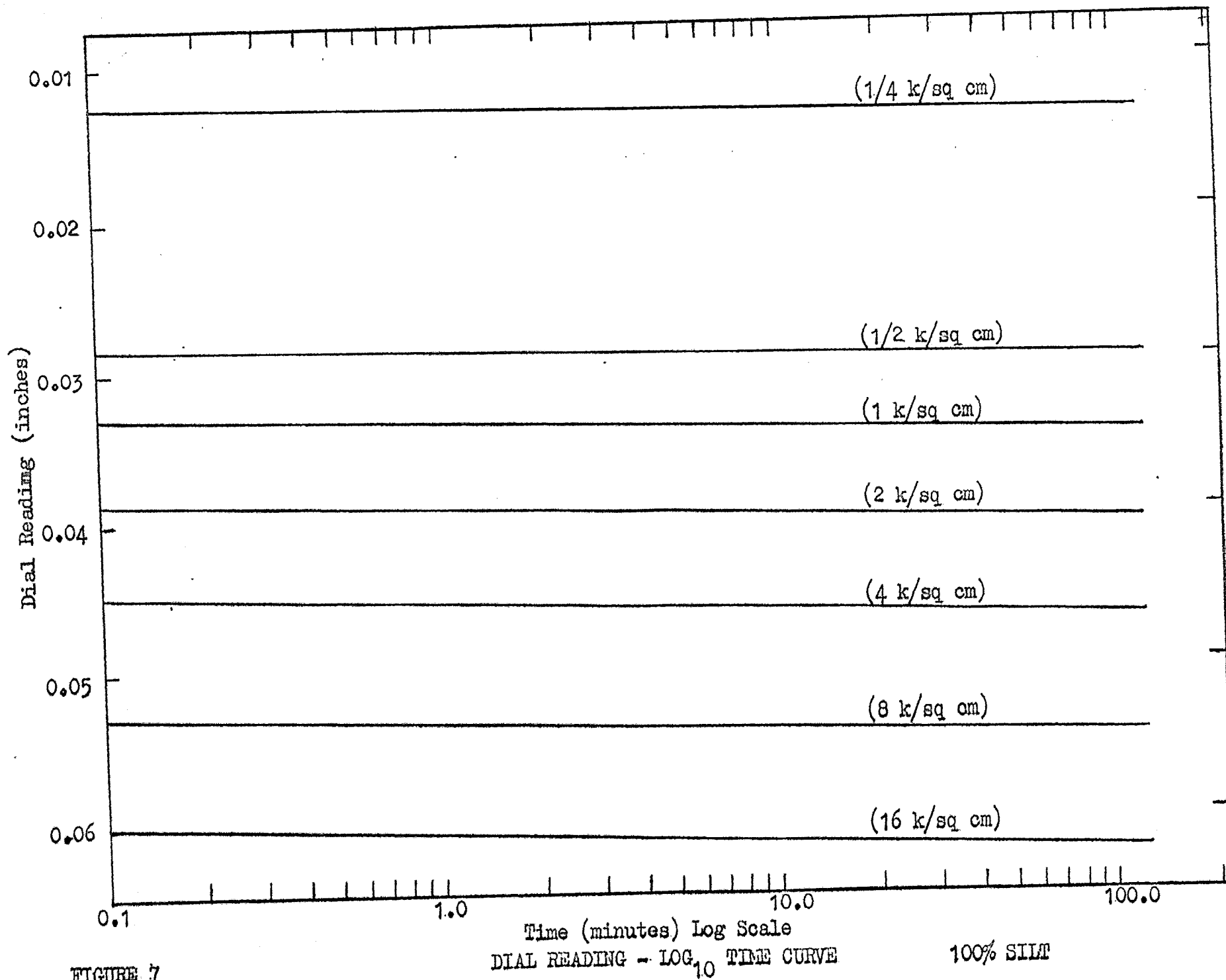


FIGURE 7